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A PLAN FOR ENSURING HIGH AVAILABILITY FOR THE SPALLATION NEUTRON SOURCE FACILITY

M. J. Haire

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6180
Tel: (423) 574-7141
Fax: (423) 574-9512
E-mail: hairemj@ornl.gov

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ACRONYMS

A/E	architect engineer
ANL	Argonne National Laboratory
BNL	Brookhaven National Laboratory
CM	construction manager
DOE	Department of Energy
E-SPEC	equipment specifications
FMEA	failure mode and effects analysis
ICS	integrated control system
LBNL	Lawrence Berkeley National Laboratory
LANL	Los Alamos National Laboratory
LINAC	linear accelerator
ORNL	Oak Ridge National Laboratory
QA	quality assurance
R&D	research and development
RMA	reliability, maintainability, availability
RAMI	reliability, availability, maintainability and inspectability
SNS	Spallation Neutron Source

EXECUTIVE SUMMARY

The Spallation Neutron Source (SNS) is a new ~$1.3B accelerator-based neutron research facility being constructed by the U.S. Department of Energy in Oak Ridge, Tennessee. The SNS provides beams of neutrons for research (a) in broad areas of physical, chemical, and biological sciences and (b) in new materials development. The SNS will be a front-line user facility and will be expected to have a high level of user satisfaction as measured by facility operating time. The Basic Energy Sciences Advisory Committee Panel on Neutron Sources, better known as the Kohn report (ref. 1) said in January 1993, "Scientific users with an accepted experimental proposal should be informed about the dates of their experiment with sufficient notice to allow for appropriate planning with regard to the availability of samples and apparatus, as well as the arrangement for travels and housing.… In particular, down periods lasting a significant fraction of a typical run time should be kept to an absolute minimum." The requirements of the Kohn report will be accomplished in the SNS by a reliability, availability, maintainability, and inspectability (RAMI) program.

In response to the Kohn Report, the SNS *Design Manual* (revision date September 25, 1998) defines facility up-time requirements in Chapter 2, Sect. 4:

- The facility shall be optimized to maximize neutron-beam availability for a minimum of 240 d/year operating schedule. This operating schedule includes tuning, machine development, normal operation (beam research), and short-term maintenance, such that ~4000 h/year are available for neutron-scattering research.

The availability requirements are established in Chapter 10, Sect. 10.2.l:

- The key operational parameter is reliability and predictability for machine performance..... [The] specified predictability is 85%.

During a particular facility run during which there is no scheduled downtime, predictability is equal to availability. For a facility to meet an 85% availability goal, each of its major subsystems must meet a much higher goal. To illustrate the implications of this, let us consider a major subsystem having a 98% availability requirement for a 4-week run. The permitted downtime for this run for this system is only 13.7 h.

The RAMI program for the SNS is applicable throughout all phases of the project. In the conceptual design phase, for example, the SNS team makes choices from among various systems design alternatives using estimates of performance based on historical data. During preliminary design, availability predictions and reliability tests provide additional information that confirms earlier choices. In the final

design, the project makes final decisions and conducts demonstration tests to assure that RAMI requirements are met. Reliability requirements are included in the equipment procurement process. During commissioning and operation, RAMI analysis are used to establish spare parts and budget for repair, shop facilities, and personnel training.

A driver in the RAMI program will be the comparison of required availability and predicted or calculated availability to determine whether the facility and its systems meet the facility requirements. This comparison is done repeatedly in greater and greater detail, and it may cause redesign of systems and subsystems. The comparison between predicted availabilities and apportioned availabilities requirements will be done at nearly every design review and will be comprehensively revisited at the conclusion of each major design phase (Title I and II), any major redesign, and major testing to ascertain if any design changes have occurred or if new information has been found that could impact achieving the SNS reliability, maintainability, and inspectability requirements. If agreement is not reached between allocated and expected availabilities, it is necessary to change the design in some way. The first phase of redesign is to identify critical items or areas for which expected availability is significantly lower than allocated availability. Subsequent redesign or elimination of a critical item in that system can significantly reduce downtime. Items so identified are then included on a “critical items list”. Some options do not require actual redesign of equipment, but simply require different maintenance procedures, training, spare parts management, etc. After the options are evaluated according to their compatibility with the SNS design requirements, cost, and schedule, the most appropriate corrective action is selected and implemented.

The approach used by the RAMI program for the SNS is:

1. Clearly define availability and predictability requirements with respect to operating philosophy
2. Establish an agreed upon set of availability allocations requirements for each subproject
3. Establish an SNS database of equipment failure rates and repair times, preventive maintenance requirements, and operating-condition monitoring devices and procedures
4. Perform analyses to determine components that are “critical” to meeting the availability requirements of the SNS project and subprojects
5. Develop designs that in past experience have led to achieving the subprojects’ availability allocations
6. Develop plans and actions to appropriately address “critical” systems and equipment and ensure that plans and actions are followed
7. Perform design reviews to assure that RAMI characteristics are properly incorporated into the design
8. Document features that show how the design of projects and subprojects will meet their availability goals
9. Include appropriate RAMI tests in the subproject acceptance tests

The project office will lead the RAMI team, take the lead role in performing Items 1 and 2, participate in project-wide reviews (Item 7), interface with research and development programs, fold reliability and maintainability information into developing operating profiles which maximize facility availability, and provide RAMI technical support to the subprojects. Each subproject will perform Items 3 through 9. The program will be implemented by a team consisting of a RAMI professional at the project office and a representative from each subproject.

Each subproject is responsible for the RAMI assessments of their own design, testing, procurement, construction, and commissioning: Lawrence Berkeley National Laboratory for the accelerator front-end source systems, Los Alamos National Laboratory for the linear accelerator systems and control systems, Brookhaven National Laboratory for ring and transfer line systems, Oak Ridge National Laboratory (ORNL) for target systems, and Argonne National Laboratory for experiment instrument systems. The Architect Engineer is responsible for conventional systems. ORNL will guide RAMI programs and integrate results from collaborating national laboratories. A substantial amount of availability data already exists from operating accelerators (ref. 2). Since dedicated reliability testing is very expensive, the SNS project will glean reliability and maintainability information from single-component, prototype, and demonstration functional tests of developmental systems.

In summary, this program plan describes the RAMI analysis engineering activities planned for the SNS. It specifies the actions necessary to fulfill the RAMI requirements, as defined in Chapters 2 and 10 of the SNS *Design Manual*. This document specifies the RAMI work plans, actions, and organizational structures necessary to accomplish successfully the design and operation of the SNS. The appendix of this plan provides a RAMI engineering guide for systems development. This document defines the top-level administration and technical requirements for planning and performing tasks from the start of the project through completion of plant commissioning and operational tests.

ABSTRACT

The Spallation Neutron Source (SNS) is an accelerator-based neutron scattering research facility being constructed at the U.S. Department of Energy's Oak Ridge Reservation, located at Oak Ridge, Tennessee. The SNS provides beams of neutrons for research in broad areas of physical, chemical, and biological sciences, as well as in new materials development. This report describes the reliability, availability, maintainability, and inspectability (RAMI) analysis activities planned for the SNS. The objective of the SNS RAMI program is to ensure that SNS meets its availability and predictability design requirements. This objective will be achieved through evaluations of equipment systems failures (reliability) and the time it takes to return the plant to normal operation once failures occur (maintainability). Guidelines for implementing a RAMI engineering program are given. The elements of a reliability engineering program also are described in this report.

1. INTRODUCTION

The Spallation Neutron Source (SNS) is a new accelerator-based neutron-scattering facility designed to provide special scientific and research capabilities to serve the needs of the nation's universities, industry, private and federal laboratories, and others involved in the development and application of neutron-based research. Neutrons are unique and increasingly essential as tools in broad areas of physical, chemical, and biological sciences and in new materials development. To complete the construction project, it is necessary that an accelerator system deliver short (microsecond) pulses of high-energy protons that are accumulated in a ring, delivered onto a target where pulses of neutrons are produced by the spallation process, and then delivered to a transport system for experiment applications. Design and construction of the facility at Oak Ridge, Tennessee, are expected to be completed in the year 2005 and to have a total project cost of ~$1.3 billion.

The SNS will be a front-line user facility and will be expected to have a high level of user satisfaction. Quantifying satisfaction is difficult considering the high degree of subjectivity in any definition of the word *satisfaction*. However, the most relevant definition is probably in the Basic Energy Science Advisory Committee January 1993 report on neutron sources, which states that, "....scientific users with an accepted experimental proposal should be informed about the dates of their experiment with sufficient notice to allow for appropriate planning with regards to the availability of samples and apparatus, as well as the arrangements for travel and housing. These dates should be respected by the facility.... In particular, down periods lasting a significant fraction of a typical run time should be kept to an absolute minimum." *Satisfaction*, from the user's perspective on facility availability and predictability, can be translated through a traditional reliability, availability, maintainability, and inspectability (RAMI) program. *Inspectability* is a recent addition to the RAM discipline and incorporates the principles of reliability-centered maintenance or equipment, health, and condition-based component replacement during facility operation. *Availability* is defined as the fraction of the year that the source is scheduled to operate for neutron research. The SNS project uses two parameters not associated with traditional RAMI programs, predictability and dependability. *Predictability* is the fraction of the time that the facility is scheduled to be performing research, that is, the time the neutron beam is actually available for research. *Dependability* is the overall ratio of hours the beam is actually delivered for research vs the number of hours scheduled for research. The difference between predictability and dependability is that the facility can reserve the right to continue operation into scheduled shutdown periods to make up for failures that may have occurred within the scheduled operating period.

This document describes the RAMI analysis engineering activities planned for SNS. It is intended to specify the actions necessary to fulfill the RAMI requirements defined in the *SNS Design Manual* (revision date, September 25, 1998). Facility up-time requirements are given in Chapter 2, Sect. 4, of the *SNS Design Manual*:

- *The facility shall be optimized to maximize neutron beam availability for a minimum of 240 d/year operating schedule. This operating schedule includes tuning, machine development, normal operation (beam research), and short-term maintenance, such that ~4000 h/year are available for neutron scattering research.*

The availability requirements are established in Chapter 10, Sect. 10.2.3, of the *SNS Design Manual*:

- *The key operational parameter is reliability and predictability for machine performance. [The] specified predictability of 85%,.... is strongly preferred over less reliable higher-power running.*

This document specifies the RAMI work plans, actions, and organizational structure necessary to accomplish successfully the design and operation of SNS. The appendix of this plan provides a RAMI engineering guide for system development. The elements described herein apply to all activities associated with the SNS project. This plan serves as a guide for those involved in subprojects who must prepare a detailed analysis of their systems.

This SNS RAMI plan defines the top-level administration and technical requirements for planning and performing tasks from the start of the project's conceptual design through the completion of the plant's operational test. This document has been prepared to satisfy the requirements defined in the *SNS Project Execution Plan*.

SNS project phases and associated schedule and major milestones are defined in the *SNS Project Execution Plan*. The project phases include research and development (R&D), safety and licensing, conceptual design, advanced conceptual design, preliminary design (Title I), final design (Title II or detailed design), procurement and construction, and acceptance test (Title III).

1.1 JUSTIFICATION

A number of unique systems will experience operation for the first time in the SNS; therefore, it is very important that these systems operate reliably. The RAMI program accelerates the maturing of emerging technology by identifying weaknesses during the design and test phases and will ensure that the SNS availability and predictability requirements are satisfied.

1.2 OBJECTIVE

The objective of the RAMI program is to ensure that the SNS meets its 85% inherent availability and 85% predictability requirements, as stated in Chapters 2 and 10 of the *SNS Design Manual*. Availability requirements are defined in two ways: operational and inherent. (Section A.1.5 of the appendix defines these in detail.) Basically, the operational requirement is established by dividing operating time by total calendar time. For SNS, the operational availability requirement is equal to the average number of operating days scheduled each year, 240, divided by 365 d/year. Inherent availability is that availability

attributed to the performance of the equipment itself (i.e., considering equipment failures) and does not include administrative or scheduled downtime. During a scheduled run, inherent availability and predictability are equal. SNS requires that 4,000 h/year be available for neutron-scattering research. The 85% predictability requirement is established by dividing the required 240-d operating time, by operating time plus corrective maintenance repair time, 42 d. As noted above, the SNS 85% predictability requirement is described in Chapter 10, Sect. 10.2.3 of the *SNS Design Manual* and forms the basis for the apportionment of overall plant availability among plant systems and subsystems. This apportionment will become the availability design criteria of subprojects, systems, and subsystems.

1.3 OPERATIONAL STRATEGY

The scientific community has stressed the importance of predictable facility operation. Thus, a central focus of the RAMI program is to ensure that SNS meets, or exceeds, its 85% predictability. Predictability, as defined for SNS, is not included within traditional RAMI analysis. To investigate predictability, one must first define an operating schedule for the facility. Simulations and assessments associated with predictability also require that an operation and maintenance strategy be assumed. The approach taken by the SNS project is to search for the operating schedule, operating and maintenance strategy, and system design features that optimize predictability. Results from these optimization studies will be available to the design team during Title I design so that appropriate design features can be incorporated.

A tentative simple plan for operating the SNS is to operate for four-week blocks, with two weeks of maintenance between blocks. See the *SNS Design Manual*, Chapter 10, Sect. 10.1.2. Thus, the 4,000 h of neutron research time, at 85% predictability, results in 4,706 h of scheduled operation. This is broken into seven blocks of four-week operation runs with six 2-week blocks of downtime between runs. This leaves a single (~12-week) block of long shutdown for a yearly maintenance period.

The time that the facility is unable to deliver a neutron beam for research during a period when such delivery is planned is referred to as “unscheduled downtime.” The severity of the impact of such unscheduled downtime is related to the length of time without beam. Note that the relevant time is not just the time to diagnose and repair the problem but also the time to restore the beam to target. There is a certain minimum time for which an interruption need not enter into the calculations of predictability and dependability, provided that they are rare enough so as not to significantly impact the total hours of beam delivery. Any beam interruption of 5 min or less shall be recorded and documented, but the interruption is not be used in calculating predictability and dependability. Any beam interruption of between 5 min and 1 h is also not used in calculating predictability and dependability, unless the total amount of such uncounted time exceeds 1 h in a 24-h period.

2. APPLICABLE DOCUMENTS

Key SNS project documents that interface with this RAMI plan are:

- *SNS Design Manual*
- *SNS Project Execution Plan*
- *SNS Quality Assurance Plan*
- *SNS Systems Engineering Management Plan*

2.1 U.S. DEPARTMENT OF ENERGY (DOE)

DOE Order DOE 0 430.1, "Life-Cycle Asset Management," provides requirements for DOE, in partnership with its contractors, to plan, acquire, operate, maintain, and dispose of physical assets (ref. 1). The Order describes the minimum process for operation and maintenance of physical assets, including the preventive, predictive, and corrective maintenance to ensure physical asset availability for planned use. At Oak Ridge National Laboratory (ORNL), the Order is implemented through performance measures reported quarterly. Requirements within the Order configures what should be done and guides describe how it should be done.

The primary guide relative to RAMI is, *Reliability, Maintainability, Availability (RMA) Planning*, document No. GPG-FM-004. Interfacing DOE guides are given in Table 2.1.

Table 2.1. DOE guides interface

Guide			
Number	**Name**	**Input from *Reliability, Maintainability, Availability Guide***	**Output from *Reliability, Maintainability, Availability Guide***
GPG-FM-001	*Project Management Overview*	"Graded" project RMA program	Project top-level objectives
GPG-FM-010	*Project Execution and Engineering Management Planning*	"Graded RMA program	System engineering plan
GPG-FM-002	*Critical Decisions Criteria*	Allocated requirements for critical equipment	Mission statement
GPG-FM-003	*Engineering Trade-off Studies*	Results of RMA analyses	Alternatives for analysis
GPG-FM-005	*Test and Evaluation*	Assessment methods and basis	Test objectives and conditions
GPG-FM-006	*Performance Analysis and Reporting*	RMA assessments	Performance measures
GPG-FM-007	*Project Risk Analysis*	Critical equipment RMA assessments	Project baselines
GPG-FM-008	*Project Work Scope Planning*	"Graded" project RMA program for critical equipment	Project baselines
GPG-FM-009	*Baseline Change Control*	Proposed corrective actions	Project baselines and changes

3. MASTER PLAN

3.1 DESIGN AND ANALYSIS

RAMI program objectives will be achieved through a concurrent engineering process involving system designers and reliability engineers working together throughout the design process (ref. 3). The task will be performed through evaluations of equipment systems failures (reliability), condition monitoring of equipment (inspectability), and the time to return the plant to normal operation once failures occur (maintainability). Implementation of this plan will be the responsibility of the SNS RAMI program leader or his or her designated alternate(s). Equipment reliability design and analysis will be performed by the responsible subproject organizations. Actual RAMI analysis will be part of each system design activity. The SNS RAMI program will be coordinated and integrated by the SNS project; the RAMI program leader will provide technical oversight.

The source of the subsystem reliability requirements for the designers will be the *SNS Design Manual*. The evaluations will be a joint effort linking system development design engineering with the SNS RAMI program. The reliability engineer will contribute a format and a discipline for the study and ask key "what if" questions that probe for failure modes and mechanisms. The design engineer will contribute detailed knowledge of the equipment system, including how it functions and copes with component failure. The result is a more thorough probing than could be done by either engineer alone and will result in a greater transfer of knowledge and perspective across normal disciplinary boundaries.

Portions of the RAMI assessment may be subcontracted. The RAMI program will specify reliability engineering design requirements through the statement of work for each subcontractual agreement. The specific RAMI program will be as delineated in the appendix of this report ("Reliability, Availability, Maintainability and Inspectability Engineering Guide for SNS Component Development Systems"). The RAMI program will be invoked as applicable in each subcontract. The contracting organization (subproject) is responsible for the quality of the subcontracted work. Figure 3.1 shows the relationship among organizations conducting RAMI assessments.

3.2 ORGANIZATION AND RESPONSIBILITIES

The responsibilities and duties of all project participants are discussed in the *SNS Project Execution Plan*. Specific responsibilities related to the RAMI program are defined in this section and Table 3.1.

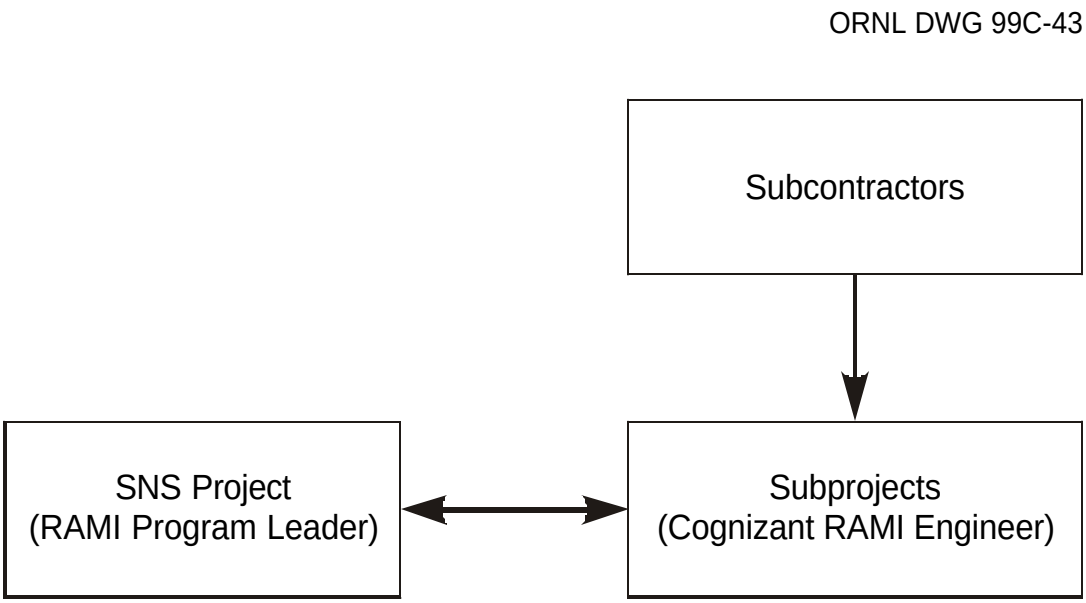

Fig. 3.1. Relationship among organizations conducting RAMI analyses.

Table 3.1. RAMI program responsibility matrix[a]

	DOE	SNS Project	LBNL[b]	LANL[c]	BNL	ORNL	ANL[d]	SNS Operations	A/E	CM[e]
Establish facility availability goals (Sect. 1.1)	A	P	S	S	S	S	C	C	C	C
Apportion facility availability among systems (Sect. 4.1.3)		A	S	S	S	P	S	C	S	C
Perform reliability assessments (Sect. 4.1.4) and identify critical items (Sect. 3.4.1)										
Front-end source systems		A	P	S	S	S	S	C	C	C
Linear accelerator (LINAC) system		A	S	P	S	S	S	C	C	C
Ring-and-transfer lines		A	S	S	P	S	S	C	C	C
Target system		A	S	S	S	P	S	S	C	C
Control systems		A	S	P	S	S	S	S	C	C
Conventional systems		A	S	S	S	S	S	S	P	C
Perform maintainability (Sect. A.3.8) and inspectability assessments		A	P	P	p	P	P	S	S	S
Component and prototype testing		A	P	P	P	P	P	S	S	S
SNS commissioning		A	S	S	S	S	S	P	S	S
Establish reliability, maintainability, and inspectability database (Sect. 3.4.2)		A	S	S	S	P	S	S	S	S
Verify that availability predictions and requirements meet (Fig. 4.3)		A	P	P	P	P	P	P	P	P

[a]A = approve, C = comment, P = perform, and S = support.
[b]Lawrence Berkeley National Laboratory
[c]Los Alamos National Laboratory
[d]Argonne National Laboratory.
[e]construction manager.

3.2.1 DOE

DOE is the owner of the SNS site and facility and has delegated overall responsibility for planning and conduct of the SNS RAMI programs to Lockheed Martin Energy Research Corp. and ORNL. DOE must approve all top-level criteria including the facility availability design requirements.

3.2.2 SNS Project

The SNS project is a collaborative effort among five national laboratories for the design, construction, installation, and commissioning of an accelerator-based neutron source. ORNL, in its role as lead laboratory, will provide overall coordination and direction for the SNS project. Lockheed Martin Energy Research Corporation, under prime contract to DOE, currently operates ORNL and is responsible for all aspects of the SNS including project management and operations. The SNS project has direct responsibility for planning all RAMI programs and interfacing with all system designers and operations. The SNS project is also responsible for establishing the overall RAMI requirements and assessment plan. The result of the RAMI analysis shall be integrated with systems design reviews and incorporated into system design, equipment specifications (E-SPEC), and equipment procurement documents, as appropriate. Recommended equipment configuration changes that result from RAMI analysis will be approved by the appropriate SNS project change control boards. The RAMI program leader is assigned to the SNS project office and is responsible for all technical aspects of RAMI.

3.2.3 Subprojects

The SNS is divided into subprojects according to the responsibilities of each national laboratory and the architect engineer (A/E) and the CM. Each laboratory and the A/E and CM is responsible for RAMI assessments for its portion of the SNS project. Each subproject will designate a RAMI engineer who is responsible for that subproject's RAMI evaluation and who is the principal contact for RAMI-related activities for that subproject. The RAMI cognizant engineer will interface with the RAMI program leader at the SNS project office in Oak Ridge.

3.2.3.1 Front-End Systems

LBNL will provide the front-end systems for the SNS, including ion source and early acceleration and transport stages. An H-beam will be produced which meets the requirements established in the SNS requirements document and properly interfaces with the control and monitoring elements and the following LINAC system. LBNL is responsible for meeting the RAMI requirements for the SNS front-end systems, as given in Sect. 4, Table 4.2 of this document.

3.2.3.2 LINAC System

LANL will provide the LINAC system required to take the beam provided by the front-end system and accelerate it to the final energy. A suitable configuration of LINACs, choppers, and diagnostic devices will be provided which meets the requirements in the SNS requirements document and properly matches to, and interfaces with, the controls and monitoring elements, with the prior front-end and with the following ring-and-transfer lines systems. LANL is responsible for meeting the RAMI requirements for the LINAC system, as given in Sect. 4, Table 4.2 of this document.

3.2.3.3 Ring-and-Transfer-Lines Systems

Brookhaven National Laboratory (BNL) will provide the ring-and-transfer-lines systems, including the transport lines between the LINAC and the target, and the accululator ring that provides the pulse compression. Systems will be designed to meet the requirements of the SNS requirements document. The ring-and-transfer-lines systems will properly match and interface with the control and monitoring elements of the prior LINAC and following target systems. BNL is responsible for meeting the RAMI requirements for the ring-and-transfer-lines systems, as given in Sect. 4, Table 4.2 of this document.

3.2.3.4 Target Systems

In addition to its role as lead laboratory, ORNL will also provide the target system of the SNS, including target, moderators, beam ports, and shielding. The target system group will also have responsibility for the three major beam dumps. Systems will be designed to meet the requirements in the SNS requirements document, and attention will be paid to interfaces, particularly to the neutron beam line. ORNL is responsible for meeting the RAMI requirements for the target systems, as given in Sect. 4, Table 4.2 of this document.

3.2.3.5 Control Systems

In addition to the LINAC systems, LANL is responsible for providing a single, integrated, plant-wide control system that will provide monitoring, and data acquisition services. This system is referred to as the integrated control system (ICS). The overall functional requirement for the ICS is to provide integrated and seamless commissioning and operation at the supervisory level among the various subproject control systems. LANL is responsible for meeting the RAMI requirements for the control systems, as given in Sect. 4, Table 4.2 of this document.

3.2.3.6 Experiment Systems

ANL and ORNL are responsible for experiment instrumentation development.

3.2.3.7 Conventional Facilities

Knight/Sverdrup Joint Venture is responsible for the A/E and CM of the SNS. The A/E is responsible to the SNS project office as the system designer for balance-of-facility systems. The balance-of-facility designer is responsible for all technical aspects of RAMI analysis for the assigned systems through completion of the project. See Sect. 4, Table 4.1 of this document for the overall design requirement for conventional systems. The CM is responsible for the planning, construction, and testing of the system before it is turned over to the facility operator. The CM will support corrections of any deficiencies discovered during commissioning test programs.

3.3 TESTING PLANS

RAMI testing will be integrated with the equipment and system R&D and testing program: single component prototype, system demonstration, and operations tests.

3.3.1 Critical Items

Critical items are those whose failure could affect significantly the ability of the SNS to achieve its availability goals. A critical items list is the result of the quantification of system reliability and maintainability; items are ranked in terms of the fractional contribution to total unavailability of each item in the system. Critical items may be subjected to life-testing. These tests will be performed by the responsible equipment system task, the program element which provides the equipment, to verify the predicted reliability of the equipment. Subcontractors may provide recommendations and suggestions for the test program as to test parameters, recommended test data, and similar inputs that would contribute to meaningful RAMI tests. The SNS project RAMI program will provide test program guidance that in turn will provide the top-level overview of the test program, facilities, and equipment required and the scope of the tests to be performed.

3.3.2 Equipment Testing

A reliability and maintainability database will be established and maintained current with system qualification, acceptance, and operability testing. The equipment system tasks, in conjunction with the RAMI program, will seek input from vendors and reliability databases to establish the requirements of, and tests to be performed on, equipment systems. Each equipment development task may conduct tests of complete systems in test facilities. Interface devices to component systems may be tested by qualified subcontractors or vendors. Testing only for reliability purposes will be minimized because it is expensive and difficult to obtain a statistically significant failure rate. Several items of the specific equipment in question must operate over a long period. Frequently, the most effective reliability test effort is devoted to monitoring the whole array of tests to obtain the most useful information from the data. Preoperational tests, commissioning, and operational tests are planned. Specific reliability, maintainability, or inspectability tests may be conducted on critical items as a necessary aspect of the overall test program.

3.4 QUALITY ASSURANCE (QA)

This document delineates interfacing reliability and quality activities according to Appendix A, Sect. A.1.4. The interfacing documents will be the *SNS Quality Assurance Program Plan* and implementing documents. The specific QA requirements will be imposed on subcontractors through the applicable contract. Design reviews are a QA requirement. Confirmation that predicted system availability meets a system availability goal is an element of the design review.

4. ELEMENTS OF THE RAMI ENGINEERING TASK

4.1 STRUCTURE

The elements of the SNS RAMI program are presented in Fig. 4.1. The figure indicates the major tasks to be performed and related subtasks. A brief description of each task follows.

4.1.1 Interfaces

The SNS project is unique in that it is a fully collaborative effort among five geographically disperse national laboratories; therefore, the interface function is especially important. Technical interfaces between and among the national laboratories and the SNS project are established by interface-definition documents. The division of responsibilities among DOE, the SNS project, and subprojects is described in Sect. 3.2 and shown in Table 3.1. Subprojects will perform RAMI assessments for the portion of the facility for which they are responsible. The SNS Project will integrate and will have the lead role in RAMI assessments and methodologies for SNS.

SNS RAMI activities will augment and closely interface with the established SNS Project support functions of QA, safety, equipment testing, and procurement. All programmatic elements and work activities of the SNS RAMI plan shall be integrated with, and executed in concert with these interfacing functions. Referencing documentation of the interfacing programs are given in Sect. 2.

4.1.2 Documentation

The objective of the RAMI program master plan is to define the general requirements of RAMI analysis to be conducted to support the SNS program. Section 5 of this report lists the major documents of the RAMI task. Additionally, quarterly progress reports will be submitted to the SNS RAMI task leader who will incorporate them into the overall project progress report. The SNS RAMI task leader will provide the appropriate distribution list for documents. Appendix A of this document provides details and guidance for implementing the RAMI plan for SNS.

4.1.3 Apportionment of Availability

The whole-facility, overall, inherent availability and predictability requirement will not change throughout the course of the project. The allocation of this overall requirement among subprojects and subproject systems will be revisited and possibly changed at the conclusion of each major design, redesign, and testing. Reallocation is the result of design trade-offs and optimization.

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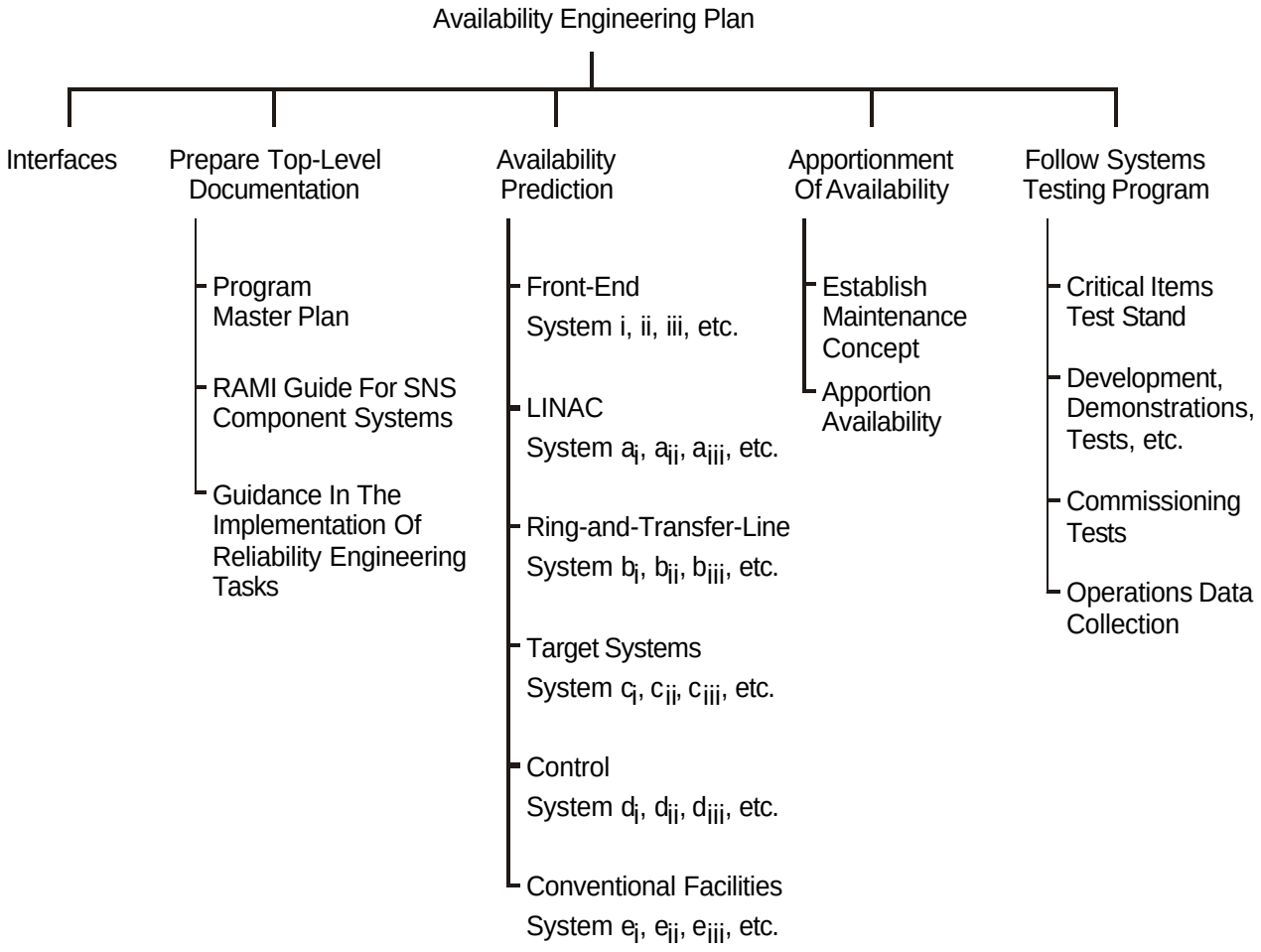

Fig. 4.1. Elements of the RAMI assessment program.

An initial availability apportionment will be performed using the overall availability requirements referenced in Sect. 1. The availability apportionment will be made using a top-down methodology based on interviews with accelerator systems experts (ref. 4). Availability requirements, distributed proportionately among the facility's systems, will be based on each system's capability for meeting the design objective. Initial estimates of overall facility availability among major plant systems will be reported, as shown in Table 4.1.

Table 4.1. Overall availability requirements for the SNS[a]

Work breakdown structure no.	Functional system	Inherent availability (%)
1.1	R&D	100
1.2	Project support	100
	Subprojects (see Table 4.2)	85
1.7	Experiment systems	100
1.9	Operations	100
	Overall facility	85

[a]Values in Tables 4.1 and 4.2 are supplied from the allocation task.

Several major categories of the SNS program are presented in Table 4.1 and 4.2. R&D is that R&D necessary to support the SNS project. The 100% availability, as given in Table 4.1, means that the project will not be delayed or interrupted by that activity. For example, R&D will identify solutions to technical problems confronting the project. Likewise, project support and operations will not delay or interrupt the project. Project support includes the administrative and management activities that integrate across the entire project, such as management, regulatory compliance, QA, etc. Operations include materials, equipment, plant maintenance, security administration, operator training, etc. required for operation. Experiment systems are instruments associated with the SNS facility research. There are 12 such major experiment systems instruments so that even if several are unavailable, providing a neutron beam enables productive research in the remaining instruments. Thus, experiment systems are assigned an availability of 100%. The RAMI program will focus on the accelerator systems, target systems, and conventional facilities, as further described in Table 4.2. Conventional facilities include preparation of the site, design, construction of buildings, and provisions of all utility systems.

Table 4.2. Subproject availability requirements

Work breakdown structure no.	Title	Availability criteria
1.3	Accelerator front end, i.e., ion source for H-beam	99.2%
	Low-energy beam transport line Medium-energy beam transport line Radio-frequency quadrapole accelerator Beam-chopping systems Etc.	
1.4	LINAC systems	96.1%
	Drift-tube LINAC Coupled-cavity drift tube LINAC Radio frequency drive systems Beam diagnostics Etc.	
1.5	Ring-and-transfer-lines systems	95.2%
	High-energy beam transport Accumulator ring systems Transport to target station Beam cleanup and scraper systems Etc.	
1.6	Target systems	94.6%
	Target Moderator systems Etc.	
1.8	Conventional facilities	99.5%
	Utilities Buildings Safety and computing systems	
1.9	Control systems	99.5%
	ICS global systems System for each subproject	
Overall		85%

LBNL is responsible for the accelerator front-end system, LANL is responsible for the LINAC and control systems, BNL is responsible for the ring-and-transfer-line systems, ORNL is responsible for the target systems, and ANL is responsible for experiment systems. Although ORNL has responsibility for coordinating and managing the collaboration, and ultimately operating the SNS, the other participating laboratories are totally responsible for designing, constructing, and integrating their respective parts of the accelerator into the final facility.

4.1.4 Availability Predictions

An availability assessment will be made for each SNS system. Detailed reliability and maintainability analyses will be conducted for selected elements of the work breakdown structure according to the critical system list (see Sect. 3.3.1). Maintenance concepts and availability apportionment studies will indicate particularly important systems. A prioritized listing of the major availability predictions will be developed.

In each of these critical systems, the RAMI program will invoke availability requirements and monitor progress through design reviews and will participate actively in the work to ensure meaningful accomplishment of the overall availability requirements. Availability prediction is the inverse process of availability apportionment. In a prediction process, measured or estimated mean time between failures and mean time to repair parts and subsystems is used as the basis for computing system availability. In an allocation, the process starts with an overall plant requirement (or goal), which is converted to an availability requirement permitted for each system. The apportionment in no sense indicates that the particular level of availability can be achieved. It merely means that if the apportioned values are achieved, the system will meet its requirements or goals.

System availability prediction models must be developed. The model must depict actual operation at each functional level—facility, system, subsystem, component—and must represent actual equipment configuration and operating modes. The starting point for developing the models is preparation of a functional diagram of each process system. This diagram is based on a thorough understanding of the SNS conceptual flow sheets and later-generation flow diagrams. Functional diagrams and flow sheets show whether functions are in parallel or series with each other and whether switching provisions are provided where redundancy exists. The availability of the entire facility often can be predicted by showing the functional relationship between systems on such a diagram. Reliability and maintainability data are input to the availability model. Figure 4.2 shows the network of RAMI analysis tasks. A variety of models is discussed in the appendix.

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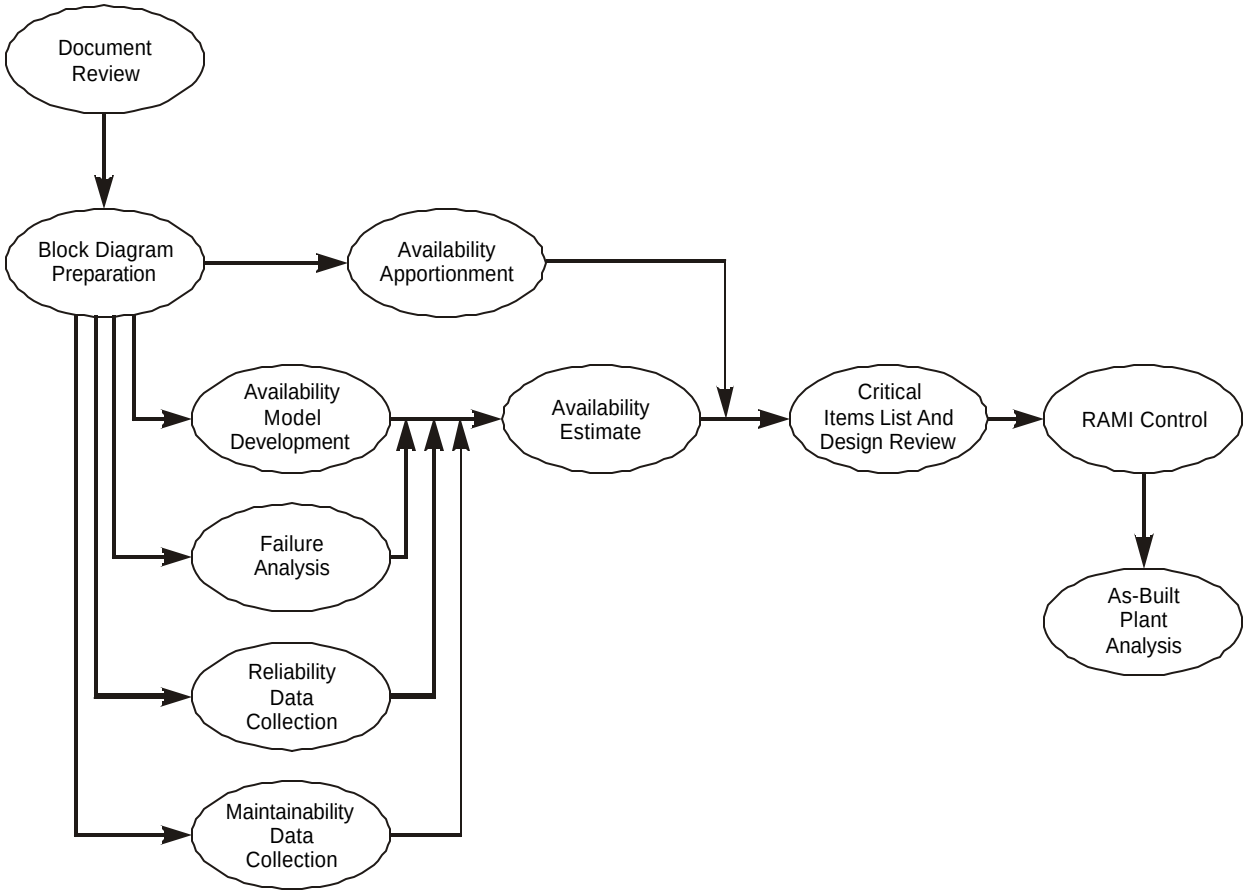

Fig. 4.2. Activity network for RAMI analysis.

Once the apportionment (target or design criteria) availability is established and an availability prediction assessment has been completed, a comparison of the two is made to determine whether the facility and its systems meet the facility goals. This assessment flow is shown schematically in Fig. 4.3. Years are required to develop the necessary data and analytical methods. Thus, this comparison occurs in the latter part of plant design. It is done repeatedly in greater and greater detail, and it may cause redesign of plant systems and subsystems. The comparison between predicted availabilities and apportioned availability goals (Fig. 4.3) will be reviewed at the completion of Titles I and II design phases to ascertain if any design changes have occurred or new information has been found that could affect achieving the SNS reliability and maintainability goals. If agreement is not reached between allocated and expected availability, it is then necessary to change the design of the facility in some way, for example, by

- Improving component quality and/or diversity
- Modifying environmental considerations
- Building in monitoring devices
- Improving ease of maintenance
- Adding redundant equipment
- Changing the equipment configuration

The first phase of a redesign is to identify the critical items or areas where expected availability is significantly lower than allocated availability. Subsequent redesign or elimination of a critical item in that system can, by analysis, significantly reduce downtime. Items so identified then are included on a “critical item list.” Finally, a design review of the critical items is implemented, and options to reduce unavailability are evaluated. Some options do not require the actual redesign of equipment etc., but they simply require different maintenance procedures, training, spare-parts management, etc. After the options are evaluated with respect to compatibility of the SNS design requirements, cost, and schedule, the most appropriate corrective action can be selected and implemented.

When the design appears to meet the availability goals, procedures are implemented to control reliability and maintainability during manufacture, construction, and initial operation. To exercise RAMI control, the following activities are required:

- Availability-related requirements are developed and incorporated into design and procurement specifications for SNS equipment.
- Inspection and test requirements during equipment manufacture and facility construction are established, and procedures are prepared and implemented.
- Preventive and predictive maintenance requirements are identified, and procedures are prepared for use during operation of SNS.
- All design changes are reviewed and evaluated with respect to meeting the SNS availability requirements.

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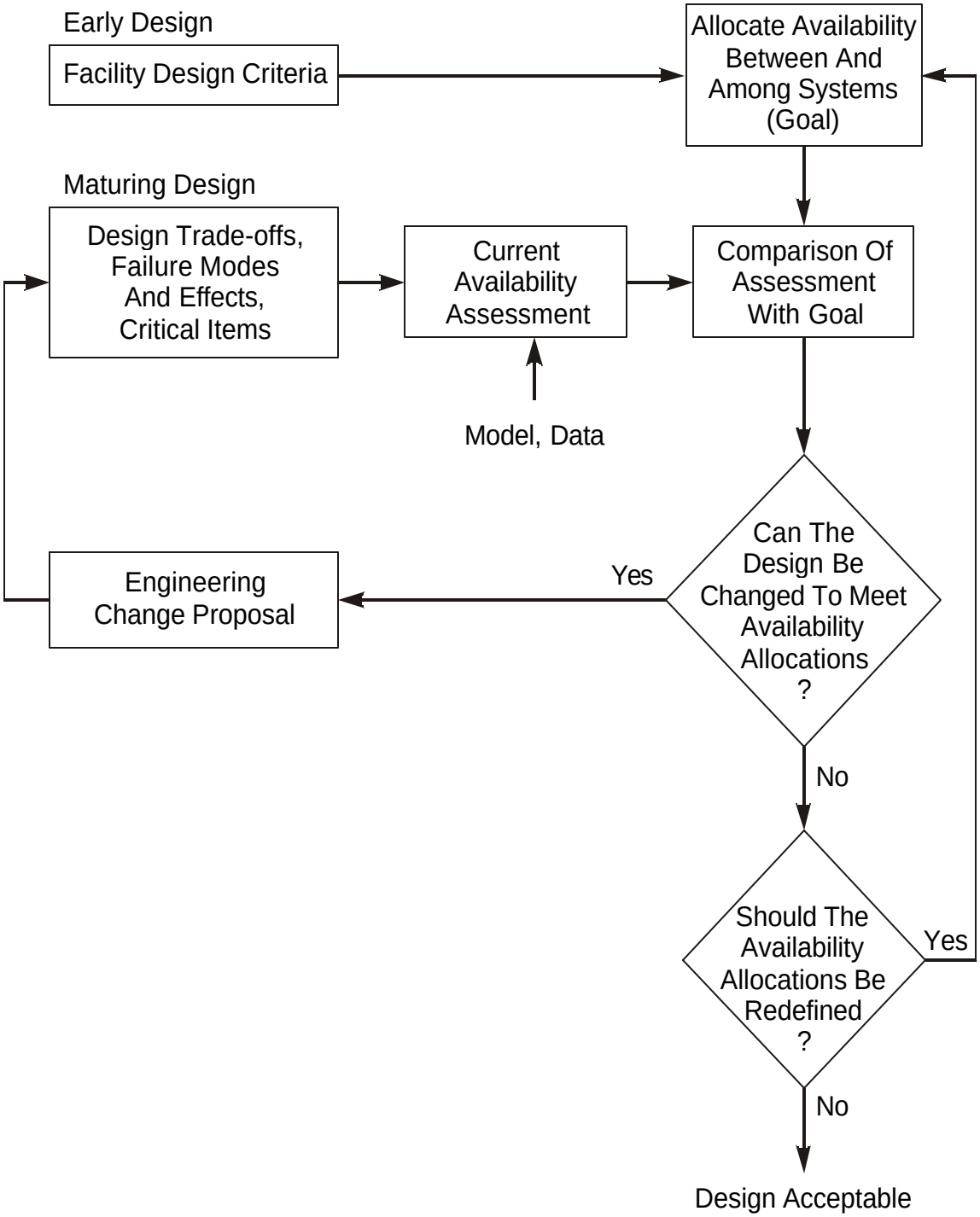

Fig. 4.3. Availability assessment flow.

4.1.5 Testing Program

Each equipment system development task is responsible for conducting test programs; the SNS RAMI program will provide guidance in the conduct of the tests. As noted previously in Sect. 3.3.2, life tests may be conducted on certain critical items. The tests shall conform to Appendix A, Sect. A.3.12 of this document.

The following suggested steps normally will occur:

- Issue a test-facility specification
- Design a test facility
- Procure test-facility equipment
- Issue a test-stand specification
- Design and build a test stand
- Install, debug, and calibrate the facility
- Issue test documents.

Additionally, each significant system activity will conduct endurance tests of the system as a whole and, combined with other systems, in the test facilities.

4.2 SCHEDULE

Figure 4.4 is the integrated SNS Project schedule as of January 22, 1999. This schedule is collapsed into the top line of Fig. 4.5, which also gives an overview of the RAMI tasks to be performed. The RAMI program for the SNS is applicable throughout all phases of the project. In the conceptual design phase, for example, the SNS team makes choices from among various systems design alternatives using estimates of performance based on historical data. During preliminary design, availability predictions and reliability tests provide additional information that confirms earlier choices. In the final design phase, the project makes final decisions and conducts demonstration tests to ensure that RAMI requirements are met. Reliability (lifetime) requirements are included in the equipment procurement process. During commissioning and operation, RAMI analyses are used to establish spare parts and budgets for repair, shop facilities, and personnel training.

Whole-facility availability predictions will be updated at the end of Titles I and II design phases. A near-term schedule of RAMI activities is shown in Table 4.3. These RAMI activities, listings, and schedules may be updated periodically or adjusted as reliability, maintainability, and inspectability assessments are completed. The scope of failure analysis and availability predictions will be specified by the RAMI program and may include entire systems, subsystems, or discrete components.

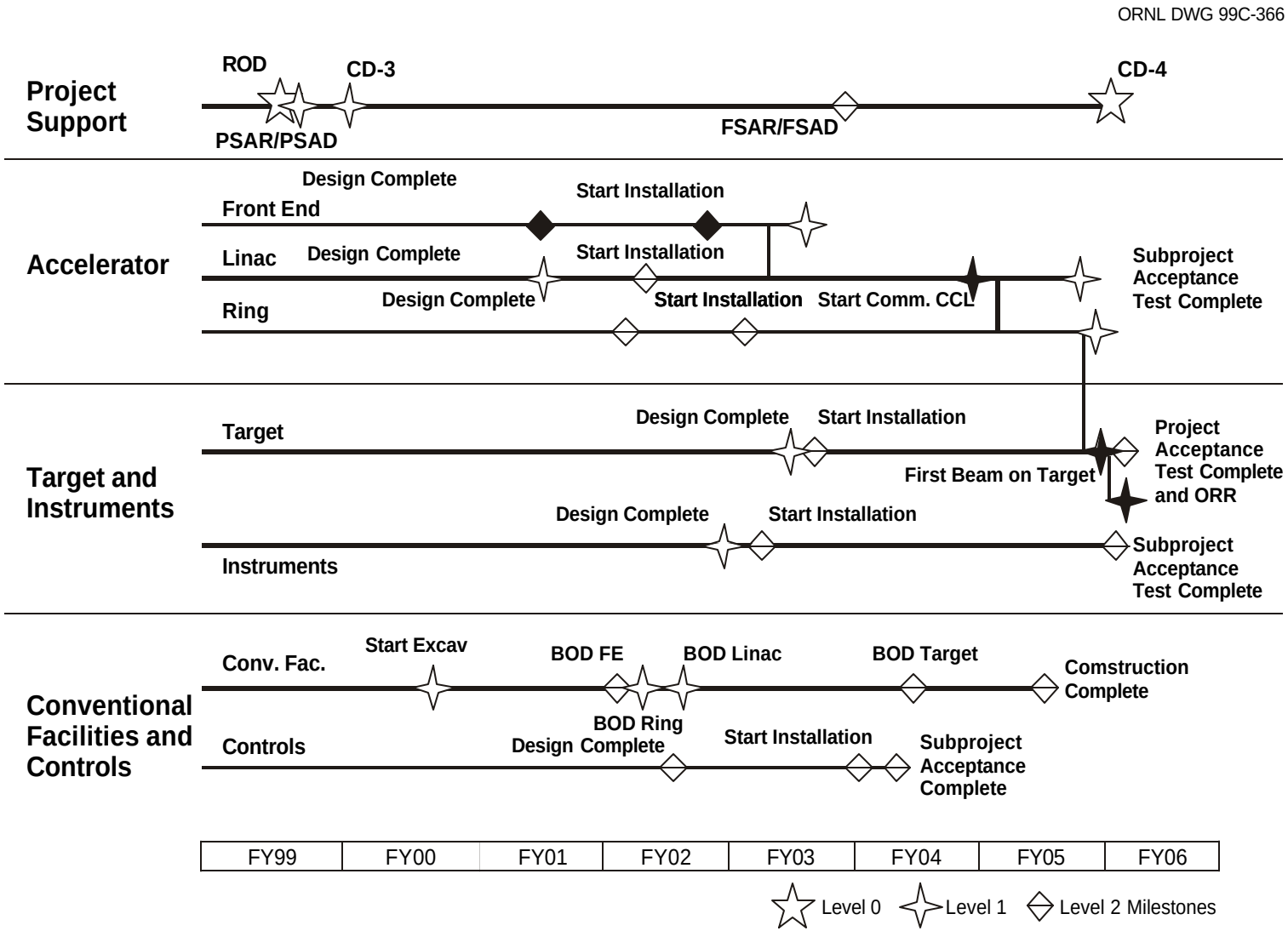

Fig. 4.4. Integrated SNS project schedule (as of January 22, 1999).

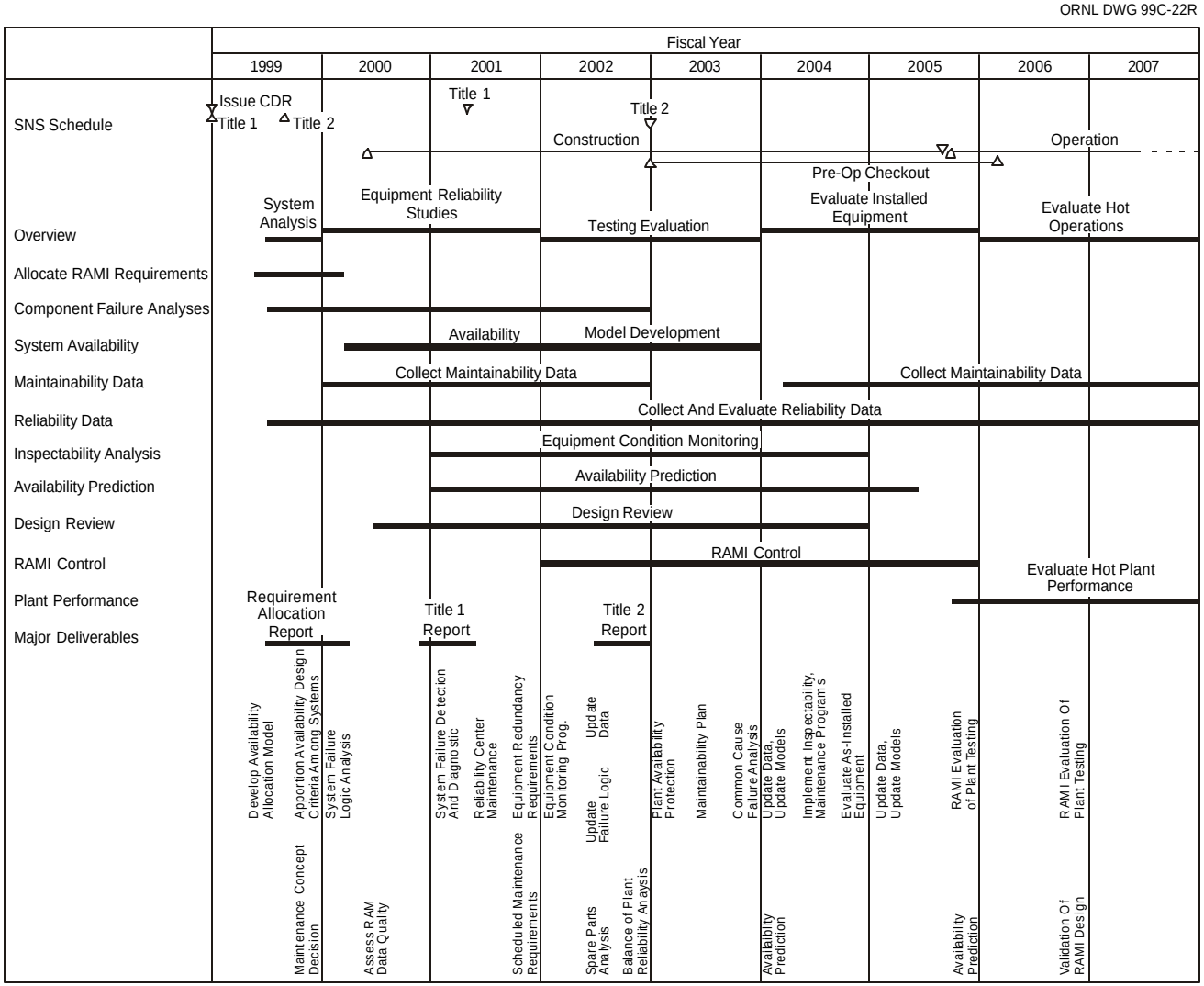

Fig. 4.5. SNS RAMI task schedule (as of January 22, 1999).

Table 4.3. Schedule of RAMI assessments (as of January 22, 1999)

	Milestone	Date
1	Quantify overall availability and predictability goals with respect to SNS operating philosophy	July 1999
2	Allocate SNS availability goal among systems and subsystems	September 1999
3	Failure analysis, prediction, and identification of critical items for each subproject:	
	Accelerator front-end systems	January 2000
	LINAC systems	October 1999
	Ring-and-transfer-lines systems	July 1999
	Target systems	March 2000
	Conventional facilities	June 2000
4	Maintenance system assessment: SNS project report	November 2000
5	Inspectability assessment: SNS project report	January 2001
6	Title 1 failure analysis, prediction, and identification of critical items, maintenance and inspectability assessment for each subproject: SNS project report (repeat Items 2, 3, 4, and 5)	May 2001
7	Title 2 failure analysis, prediction, and identification of critical items, maintenance and inspectability for each subproject: SNS project report (repeat Items 2, 3, 4, and 5)	October 2002
8	Commission testing failure analysis, prediction, and identification of critical items, maintenance and inspectability for each subproject: SNS project report (repeat Items 2, 3, 4, and 5)	December 2005

4.3 MEETINGS

Maximum use will be made of telephone, teleconferences, electronic mail systems, world wide web RAMI task sites, and individual visits to minimize the effects of disperse geographical location of participants. However, periodic (possibly annual) team meetings of cognizant persons participating in RAMI activities are anticipated.

The status of RAMI activities will be reported during the fall and spring DOE SNS project review meetings.

5. DELIVERABLE DOCUMENTS

The following documents containing RAMI assessments will be released during the design phases:

- *Initial RAMI Assessments and Availability Allocations for SNS*, June 2000
- *The SNS Maintainability Assessment*, November 2000
- *The SNS Inspectability Assessment*, January 2001
- *The SNS Plant Availability Assessment* (at the end of the Titles I design phase), May 2001
- *The SNS Plant Availability Assessment* (at the end of the Titles II design phase), October 2002
- *The SNS Plant Availability Assessment* (at the end of the commissioning design phase), December 2005

These assessments will present and include discussion of the results of all analysis and tests conducted that show compliance to the RAMI requirements. Each subproject will contribute its portion to the overall report.

6. REFERENCES

1. W. Kohn, *Neutron Sources for America's Future*, Report of the BESAC Panel on Neutron Sciences, DOE/ER-0576P, January 1993.

2. C. M. Piaszczyk, "Operating Experiences at Existing Accelerator Facilities," *Proc. NEA Workshop on Utilization and Reliability of High-Power Accelerators, Mito, Ibarak-keni, Japan, 13–15 October, 1998*.

3. W. G. Ireson, C. F. Coombs, Jr., R. Y. Moss, *Handbook of Reliability Engineering and Management*, 2nd ed., McGraw-Hill, New York, New York, 1995, ISO 0-07-012750-6.

4. M. J. Haire, J. G. Maltese, "A System Availability 'Top-Down' Apportionment Method," pp. 306–314 in *Proc. Annual Reliability and Maintainability Symposium*, Philadelphia, Pennsylvania, Institute of Electrical, Electronic Engineers, January 22–24, 1985.

Appendix A

RAMI ENGINEERING GUIDE FOR SNS COMPONENT DEVELOPMENT SYSTEMS

Appendix A: RAMI ENGINEERING GUIDE FOR SNS COMPONENT DEVELOPMENT SYSTEMS

A.1 INTRODUCTION

A.l.l SCOPE

This appendix provides guidelines for implementing a RAMI engineering program. It contains information on the various reliability engineering disciplines or tasks and supplies a basis for the RAMI program to determine what studies are to be performed and documented. The reliability disciplines involved may be directed toward matters of safety-related reliability and operating availability or maintainability.

A.1.2 APPLICABILITY

This appendix applies to those efforts that involve design, development, fabrication, testing, and modification of component systems for SNS. Specifically, this appendix applies to those systems and related components whose satisfactory performance is required for operation, inspection, maintenance, and unplanned servicing of the SNS.

A.1.3 METHOD OF APPLICATION

This appendix describes elements of a reliability engineering program. The RAMI program will provide guidance on which reliability engineering tasks will be required for the component development systems. In accordance with this document, the RAMI program will determine the specific reliability engineering tasks to be accomplished and the results to be documented.

The SNS RAMI program will implement this appendix in all phases of the component development program including design, development, testing, and fabrication. Where necessary, the SNS RAMI program will impose all or portions of this appendix on selected subcontractors.

Reliability design goals or requirements will be specified and controlled through approved RAMI program documents. The types of documentation to be used for this purpose are a process design requirements, system design documents, and E-SPEC.

A.1.4 RELATION TO QA

The RAMI engineering program is an adjunct to, and directly dependent on, the existence of effective QA activities. The RAMI program will provide the requirements necessary to ensure that component equipment reliability is not compromised during any phase of the project. All QA documents pertaining to RAMI activities shall relate to the *QA Program Plan*. Those QA requirements that apply to subcontractors will be specified by the RAMI program in the statement of work. RAMI documents should be used in conjunction with the QA requirements document and other applicable standards and codes. These documents shall also delineate interfaces and specify the method of implementation and related responsibilities. To avoid duplication of effort for those activities covered by both, interfacing reliability and quality activities will be coordinated by the SNS Project RAMI program.

A.1.5 DEFINITIONS

A.1.5.1 Availability

The characteristic of an item is expressed by the expected fraction of time it will be operational (i.e., time to perform its specified functions). Availability measures are concerned with both reliability and maintainability.

A.1.5.2 Inherent Availability

The best measure of equipment performance is inherent availability. For components, it is defined as operating time divided by operating time plus repair time. Or, it is defined as mean time between failures divided by mean time between failures plus mean time to repair. Note that such occurrences as administrative downtime and preventive maintenance are not time elements in this definition. The plant inherent availability applies most directly to those days during which neutron production is scheduled, that is, the facility state associated with delivering a neutron beam for research. For this facility state, it is defined as operating time divided by operating time plus downtime. It excludes other facility states such as scheduled replacement of components and maintenance, and administrative downtime. An overall plant inherent availability can also be defined, which is the weighted average of the inherent availability for the facility during all its states. Documentation associated with allocation of inherent availabilities to facility systems (see Sect. A.3.2) explains more fully how plant inherent availability will be defined and used for the SNS.

A.1.5.3 Operational Availability

Operational availability is defined as operating time divided by total calendar time.

A.1.5.4 Maintainability

Maintainability is the characteristic of design and installation expressed as the probability that an item will be returned or restored to a specific condition within a given period when maintenance is performed in accordance with prescribed procedures and resources. Maintainability measures are concerned with the expected duration of an outage.

A.1.5.5 Reliability

Reliability is defined as the characteristics of an item expressed by the probability that it will perform a required mission under stated conditions for a stated mission time. Reliability measures are concerned with the expected frequency of failure.

A.1.5.6 Inspectability

Inspectability is defined as that characteristic of design that allows in situ monitoring of equipment performance in regards to the amount of usable lifetime remaining. This includes the accessibility to equipment, removable coupons to determine material degradation, and diagnostics to determine incipient failure.

A.1.5.7 Predictability

Predictability is the fraction of the time that the facility is scheduled to be delivering a neutron beam for research, that is, that the neutron beam is actually available for research.

A.1.5.8 Dependability

Dependability is the overall ratio of hours that the beam is actually delivered for research vs the number of hours scheduled for research. The difference between dependability and predictability is that the facility may choose to continue operating into scheduled shutdown periods to make up for failures that may have occurred within the scheduled operating period.

A.1.5.9 Failure

Failure is defined as termination of the ability of an item to perform its required function.

A.1.5.10 Common Cause Failure

Common cause failure refers to multiple failures that are attributed to a common cause.

A.2 MANAGEMENT ELEMENTS

The SNS project RAMI program leader will develop, implement, and control component reliability engineering activities as a coordinated effort between the SNS project and subproject activities. The SNS project RAMI program will assist in organizing and training of personnel, planning and implementing reliability engineering activities, preparing and approving required documentation, and performing program control evaluations and audits. Subprojects will appoint a cognizant reliability engineer who will be responsible for RAMI assessments of the subproject.

A.2.1 ORGANIZATION

The organizational structure, functional responsibilities, and lines of internal and external communication for the management and execution of RAMI engineering activities shall be documented in the RAMI program plan, as specified in Sect. A.2.3 of this appendix. RAMI engineering activities will be led by personnel who are familiar with, and who have demonstrated proficiency and skill in, reliability engineering. The specific organizational approach to be used in implementing reliability engineering shall be established in the RAMI program plan.

The RAMI program personnel will provide knowledge of RAMI analysis methodologies, and equipment systems designers will provide detailed design knowledge of their respective systems. RAMI assessments will be a cooperative effort among SNS project, subprojects, and design and operations engineers.

A.2.2 INDOCTRINATION AND TRAINING

Indoctrination and training shall be provided to familiarize personnel with the applicable standards and reliability engineering practices to be used and with guidance regarding limitations and applications of these standards and practices.

A.2.3 RAMI PLAN

RAMI engineering activities will be planned and implemented as an integral part of design. The RAMI plan describes the work plans and actions to be performed during the course of the program and the organizational structure required to accomplish this work. All technical activities, design reviews, approvals, and reference to the RAMI requirements will be included and specifically identified in the plan. An index identifying the procedures to be used in conducting the tasks also shall be included in the plan. The plan shall be submitted for review and approval. The RAMI plan will be kept current during the life of the program.

The reliability activities will be implemented in accordance with established practices and procedures delineated in the RAMI plan description. The elements describing reliability engineering activities are included in Sect. A.3 of this appendix and will form the basis for component systems program practices and procedures. All reliability engineering activities, including assumptions and results, will be documented.

In instances where equipment design or development is performed by a subcontractor, the subcontractor must describe what reliability assessments will be made and how they will be conducted. The RAMI program will incorporate reliability requirements in the statement of work for the subcontractor.

A.2.4 RELIABILITY PROGRAM CONTROL

The SNS RAMI program management routinely will evaluate the status and adequacy of the reliability engineering activities. The evaluation will verify achievement of the required levels of reliability, meeting of requirements, and the effective implementation of the necessary follow-up and corrective actions. Findings will be documented. The SNS project, in conjunction with the SNS RAMI program, will review the reliability engineering tasks to ensure that the practices and procedures used are in accordance with accepted practices.

A.2.5 SUBCONTRACTOR CONTROL

Purchased equipment and services will be subject to the reliability requirements. The SNS RAMI program will be responsible for the reliability related specifications of the total purchased equipment and will determine to what extent the reliability requirements will be passed on to the subcontractor. The RAMI program, in liaison with QA and quality control, will arrange reviews to provide assurance of subcontractor performance concerning equipment reliability.

A.2.6 SNS RAMI PROGRAM ACTIONS

All subcontractors will be subject to inspection, evaluation, and audit by the SNS RAMI program at any time during the course of the program. In the statement of work to the subcontractor, the RAMI program will indicate the estimated occurrence of these audits. Upon request, the subcontractor will furnish, or provide access to, contract-related reliability engineering information, documents, records, and other items required by the RAMI program. The RAMI program will have access to the subcontractor's plant, facilities, and equipment work, materials, and tests related to the contract.

A.3 TECHNICAL ELEMENTS

This section describes several interrelated tasks which, when selectively implemented into project activities, will provide the reliability engineering techniques necessary in the design, development, fabrication, test, installation, operation, and modification phases of an equipment component development program. The results of such techniques are intended to provide a basis to ensure that the component equipment meets the reliability requirements or objectives, or both, and to establish the requisite confidence in obtaining safe operation and acceptable on-line availability of the system.

This section delineates specific reliability requirements, techniques, or tasks the RAMI program may select as appropriate. As an alternative, the RAMI program may request a subcontractor to review the tasks and propose those tasks that the subcontractor considers necessary to meet the reliability requirements and objectives. Figure A.1 is a block diagram giving some references associated with specific tasks. Appendix B provides reference material keyed to Fig. A.1.

A.3.1 AVAILABILITY REQUIREMENTS AND GOALS

An availability requirement is mandatory, and compliance must be demonstrated. An availability goal is a target that serves as a focus for design and operation of the equipment. It depends on a combination of analytical techniques and available test data for confirmation, but it does not require formal demonstrations. In some cases, the RAMI program may choose to use both objectives and requirements—for example, specify an objective in terms of the probability of failure confirmed by a reliability analysis and specify that a demonstration run can be performed.

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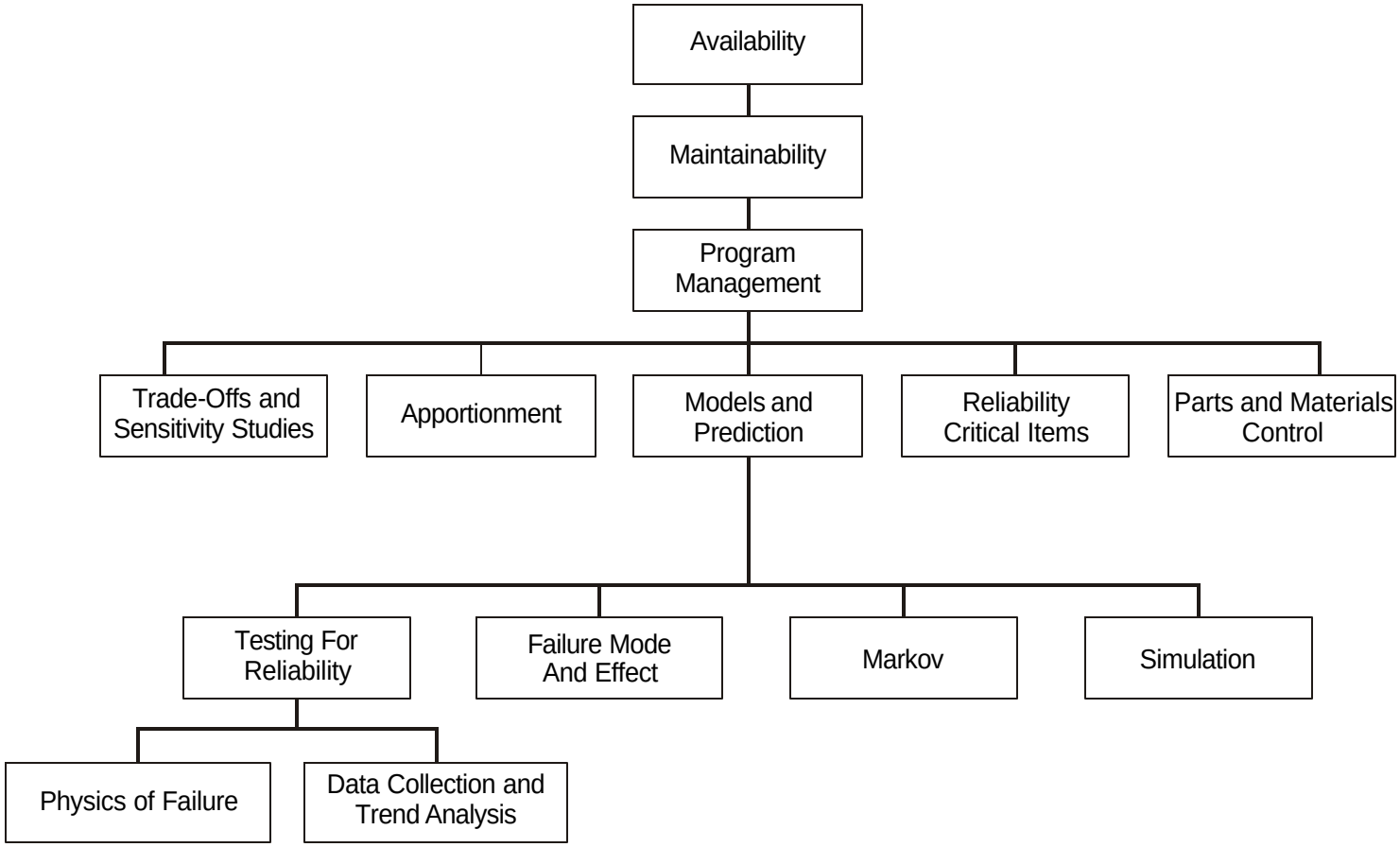

Fig. A.1. Elements of the RAMI program.

This appendix does not stand alone but depends on other documents to provide availability requirements and objectives and other necessary information. Availability requirements or objectives or both will be defined in the facility design requirements, system design documents, or E-SPEC prepared for each equipment system, subsystem, or component. The specifications will define the necessary requirements including functional, performance, environmental, reliability, safety, design life, and others. The system design documents and facility design requirements will describe system operation, define system failures, and determine the equipment and components that must be operable to perform specific system functions. The documents shall be specific in delineating system and equipment reliability requirements and objectives and shall be upgraded continually in the course of the program.

A.3.2 APPORTIONMENT

Apportionment is the assignment of top-level quantitative RAMI requirements or objectives or both to the lower-tier elements of the overall facility. Values initially assigned to the most practical lower-level elements (e.g., major subsystems) will, as the design matures, eventually result in an appropriate requirement or objective for each element in the design. Apportionment is a continuous process during design and development, with subsequent reallocation interactions as further information regarding the contribution of the various system elements to the top-level requirement or objective becomes available. The apportionment should be based on factors such as design complexity, sensitivity analysis, importance of function performed, environmental considerations, and previous experience. Apportionment, when coupled with prediction, provides the information for evaluating whether stated requirements or objectives are achievable, enables the selection of alternate viable configurations, identifies reliability problem areas, and provides information for redirection of the program into more productive areas when necessary. The procedure for coupling, or comparing availability design requirements with predicted availability, is shown in Fig. 4.3. Frequently, apportionment and trade-off studies go together so that the overall goal is apportioned in a manner that will optimize some other important parameter, such as total cost or number of independent equipment systems. For this reason, apportionment and trade-off studies are best done early in the design stage while configuration changes are possible. Unless this preliminary work is performed, the RAMI program and system designer should be alert to stated availability goals that are not compatible with the required systems configuration and state-of-the-art design. The overall tasks of apportionment, especially when exercised with trade-off studies, require an analyst with a high degree of skill and experience.

A.3.3 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

FMEA is performed to identify all significant component failure modes and the effects of failure on the operation of the system. It is an iterative process of a systematic nature for proceeding item-by-item through the system, from lower levels through the higher levels of assembly, to assess failure consequences. The FMEA may use either actual failure modes from vendor field data or hypothetical failure modes derived from design analyses, reliability prediction activities, and experience relative to the manner in which components may fail. The failure modes are analytically deduced for each component, and failure effects are evaluated and noted, including severity and expected frequency (or probability) of occurrences. Test results also are used, when available, to augment the analytical findings.

The FMEA is the basis for many of the reliability engineering tasks described in Sect. 4 and is almost always performed, although it may not be formally documented for publication. Throughout the course of a system design, the FMEA should be reviewed and updated to reflect design changes and new sources of information from vendors, field data, or tests.

The FMEA may well require the most effort of any single reliability task in the list of tasks. However, a well-done FMEA likely will save subsequent effort and avoid errors in the performance of other tasks. By determining the effect of failures on the total system, the FMEA can support appropriate studies in the areas of safety-related reliability and operating plant availability and related studies in maintainability. It provides the information needed to prepare a model and carry out apportionments, trade-offs, and sensitivity studies. Although the FMEA is basically a single-failure analysis and may be used to satisfy such a requirement, it also provides an excellent background for common-cause failure analysis, especially if extended by consideration of the failures cascading into secondary failures.

Top-level or system-level FMEAs are performed to evaluate the consequences of system-level failures. Lower-level FMEAs are performed to evaluate the consequences of lower-tier failures and may be justified only when the system-level-failure consequences are unacceptable.

Frequently, the FMEA is a joint effort linking design engineering with reliability engineering. The reliability engineer can contribute a format and discipline for the study and ask key “what if” questions probing for failure modes and mechanisms. The design engineer contributes his or her detailed knowledge of the equipment system, including how it functions and how it copes with component failure. The result often can be a more thorough probing than could be done by either engineer alone and a greater transfer of knowledge and perspective across the normal disciplinary boundaries.

Typically, the FMEA generates many pages of material on large-sized worksheets. Reducing this to a readable format for publication is a major effort, and the expense may not be warranted because of the rather limited readership. In lieu of full formal publication, the RAMI program may choose to publish only the information that leads to an identification of the "reliability critical items" in summary form as formal documentation. In this event, the original worksheets become a part of the design record file and are subject to QA audit, as applicable.

A.3.4 MODELS AND PREDICTION

A model is a logical way of showing the interrelationships between the items that make up an equipment system and the attendant response as a result of failed items and other events. Many equivalent ways exist to model a given system, the most popular being event-tree analysis, fault-tree analysis, reliability block diagrams, truth (or state) tables, and Markov state diagrams. Any method that depicts relevant information in a form that is condensed, logical, and accurate is acceptable.

Models are used to relate the arrangement and operational configuration of systems to those factors that impact RAMI. Development of the model requires design evaluations of the system characteristics. Its basis will be the collection and analysis of data combined with failure modes relating system and equipment failures to environmental parameters, fabrication, testing, operation, and maintenance factors. The model is formulated to facilitate quantitative assessments of the equipment systems as they develop to define a basis for developing design improvement recommendations and to provide a capability for measuring system reliability status vs the reliability requirements and objectives.

Prediction is the quantitative assessment of the RAMI of a system during its design, development, and preoperational stages. It is a continuous process used to provide evidence that requirements and objectives will be met. Prediction is obtained by determining the RAMI of the lowest system level and proceeding through intermediate levels until the total system is reviewed. The prediction is based on appropriate logic diagrams, mathematical models that are time oriented, failure rates, failure probability distributions, environmental factors, test intervals, repair (renewal) rates, repair distributions, and system operating profiles. Factors to be included in the prediction are functions, duty cycle, failure modes, minimum acceptable system configuration, and others. The prediction is compared to the apportioned values to determine whether requirements and objectives are met.

In general, accurate predictive calculations for models are time-consuming and expensive. Because data used in the prediction may be highly uncertain, an analysis of the propagation of uncertainties may be useful. The analyst may make approximations and simplifications if it can be shown that they do not reveal bias or invalidate the result. Someone highly skilled in reliability assessment should direct the work and interpret the results.

A.3.5 MARKOV ANALYSIS

RAMI analysis can be complicated since it should include the effects of interactions among systems and repair policies, maintenance procedures, spar parts policies, etc. It is not just the failure event but the continuing sequence of failures and repairs. For example, from an initial state, the system deteriorates to less than perfect status until failure finally occurs; then there is repair to less than as-good-as-new condition, and then deterioration again until failure again. (Inspectability capabilities can monitor the health of the component before incipient failure.) The probabilities of the system evolving from its initial state, during which all components are fully operational, to final equilibrium state, and passing through all the intermediate time-dependent positions is tracked by a set of differential equations. These are solved as a function of time for the calculation of mission reliability for a given length of mission. Markov processes describe systems having reached equilibrium.

A model of a system such as the SNS is complex. The number of states grow very fast with the number of components. For example, for 100 components with two states (fully operational and failed), the number of states is $2^{100} = 1.3 \times 10^{30}$. In practice, an approximate approach in which a reparable system is divided into subsystems, assemblies, and blocks which can be represented by a single elementary Markov process works rather well.

A.3.6 SIMULATION ANALYSIS

Simulation models are structured in the time domain during which the flow of events can be observed and evaluated (e.g., the continuous flow of air across an airfoil). In discrete or network evaluation simulation, on the other hand, time is not incremented in small, equal-sized steps, but in irregular steps, which mark events. The start and completion times of all events are modeled, but elapsed time during individual task execution is not explicitly represented. Traditional RAMI analysis has difficulty with time dependence and the handling of interaction among subsystems. Weaknesses in classical RAMI analysis are alleviated when network simulation task-based modeling is used to reproduce phenomena likely to occur in

actual system performance. Tasks or operations are modeled as discrete chronological steps; decisions are modeled that determine the path followed after completion of each task. The result is a complex logic diagram or network. The model is programmed into a computer, and computer runs are made representing time-dependent equipment operation. RAMI information (e.g., time to failure, repair times) and other performance measures which have an impact on equipment design are inputted to the simulation model. Simulation modeling starts at time zero, and an entity moves through the logic network diagram until failure occurs in a subsystem component. After the failure is repaired, the simulation continues until the next failure. Performance measures, e.g., number of failures, total downtime, total operation time for equipment, subsystem, and system, are monitored and collected during the computer run. The simulation stops after a predetermined time period has elapsed.

Monte Carlo simulation methods are numerical methods which allow the solution of mathematical and technical problems by means of system probabilistic models and the use of random variables. This method uses the statistical distribution of mean time between failure and mean time to repair, which are sampled randomly, to predict subsystem and system performance. This technique by itself is not chronologically time dependent.

A.3.7 TRADE-OFF AND SENSITIVITY STUDIES

Trade-off studies are analyses of alternate equipment designs for comparing the relative RAMI of each viable alternate or configuration. The studies are conducted relative to mechanical, electrical, and thermal considerations; component quality; redundancy and diversity; built-in test equipment; ease of maintenance, and other considerations that may be defined in the course of design and development.

Trade-off reliability studies usually are performed at the time the system configuration is being selected and in conjunction with the apportionment of overall goals. Thus, it is generally a task performed early in the design process. However, on highly developmental systems, configuration changes occasionally occur relatively late in the design cycle because of unforeseen difficulties in hardware or process development. Thus, it may be advantageous to keep the models current for this contingency.

These studies require not only an expertise in modeling but also a knowledge of equipment and cost. For this reason, they are best conducted as a cooperative effort between design and reliability engineering. In addition to providing a comparison of viable alternates, the trade-off studies provide information on the reliability-sensitive factors of the design and identify potential problem areas.

A sensitivity study is performed to determine the relative importance of the variations that can occur in a given function caused by changes in one or more parameters. Component failure rates, test intervals, repair times, etc. may be assessed to determine the effects on system reliability and availability. Then, the weakest elements may be identified and appropriate corrective action implemented.

Sensitivity studies are performed to fine-tune the design, to identify additional reliability critical items, and to identify areas of over-conservative design that are not cost-effective. They also may be used to optimize goal apportionments or trade-offs. After the design configuration is firm, sensitivity studies may be used to determine surveillance intervals and appropriate stocking levels of spare parts and to optimize repair activities. Sensitivity studies may be performed by a person of modest skill under competent supervision after the model and prediction tasks are done.

A.3.8 MAINTAINABILITY

Maintainability analysis provides the design and operational bases for ensuring that all required maintenance actions are complete and efficient and that they do not degrade the reliability or availability characteristics of the system. From analysis, maintenance information is developed for identifying limited-life items whose characteristics are incompatible with design-life requirements, establishing spares provisioning, establishing schedules and procedures to accomplish the preventive maintenance tasks at regular intervals, and establishing the maximum times for completion of maintenance actions. Maintenance considerations allow for reasonable ease of item repair or replacement, capability of on-line repair whenever possible, and performance of the actions within existing capabilities of personnel and equipment. Maintenance features provided primarily to enhance overall plant availability shall be examined carefully to avoid potential degradation of safety-related reliability. Maintainability analysis is performed simultaneously with, and as an adjunct to, the various reliability engineering tasks described in this document.

A.3.9 AVAILABILITY

Availability analysis is used to determine the probability of a reparable system being in service during a scheduled operating period. In this application, a reparable system is one that is restored to service after a failure has occurred. Both availability and maintainability apply to reparable system analyses. In a reparable system, availability and maintainability assessment is a form of probability analysis that is very similar to that used for assessing the reliability of a system not intended for repair and restoration to service.

A.3.10 COMMON-CAUSE-FAILURE ANALYSIS

Common-cause-failure analysis is used to identify events that could result in the simultaneous disabling of two or more independent equipment systems within a given critical time span. The results of common-cause failure analysis are used to identify equipment functional deficiencies and design weaknesses and ensure that design diversity is used to the extent required to reduce the probability of common cause failures affecting redundant items.

A.3.11 PHYSICS OF FAILURE

The physics-of-failure investigation is performed to determine (a) what initial or induced nondestructive defects can be introduced into a part using the operating environment and (b) the subsequent resulting failure modes. The physical mechanism by which a defect is introduced and the physical mechanism by which failure occurs are determined by this process. Physics-of-failure investigation is most useful in ultimately solving recurring failures in field or test experience. For physics-of-failure analysis, the scope of analysis shall be defined by the RAMI program.

A.3.12 TESTING FOR RELIABILITY

Confirmation of analytically derived reliability and maintainability assessments and validation of design modifications based on such assessments are conducted in part by an analysis of test data. To the greatest extent possible, testing only for reliability purposes will be minimized (a) through the examination of data from operating experience and data from existing tests or (b) by appropriate test modification. However, as a necessary aspect of the overall test program, specific reliability or maintainability tests will be conducted for certain key critical equipment items.

A.3.12.1 Test Program Elements

A.3.12.1.1 Test Planning and Integration

Test data required either for analytic inputs or for validation of results will be identified or scheduled as early as possible in the program. All planned tests are examined to determine which ones may yield this information. The schedule and nature of development, qualification, and acceptance tests are sources of reliability data. If minor modifications or additions to existing tests allow extraction of the desired information, recommendations for such changes are made. In making such recommendations, considerations are given to potential dilution of the original test purpose, effects on test schedule and cost, and the existence of alternate, more efficient test data sources or procedures.

A.3.12.1.2 Test Data Review

Test data are systematically reviewed for possible reliability and maintainability implications. These data may include detection of unanticipated failure modes, common-cause failures, single-point failures, deterioration in service, deviations from analytical assessments, and design improvement potential.

A.3.12.1.3 Test Plan

A test plan specific to each component development test shall be prepared by the responsible task. The test plan shall consist of a flowchart, diagram, or narrative description of all test activities. The plan shall identify and schedule the required tests, schedule the review of test data; summarize the purpose of each prescribed test (e.g., the characteristic to be measured, method of measurement, and applicable acceptance criteria); and use other information as appropriate. The test will present a summary of all planned test activities and their various interrelationships.

A.3.12.1.4 Test Procedure

Detailed test procedures will be prepared by the performer. Major paragraphs of the procedure shall include the following:

- Purpose
- Applicability
- Reference equipment
- Detailed implementation procedures
- Acceptance criteria

A.3.12.1.5 Test Notification

All tests performed by a subcontractor may be witnessed by the RAMI task members at any of the facilities used by the subcontractor. However, the choice by the RAMI task group not to witness any test will not be construed as a waiver of that test. Advanced notice of the initiation of the prescribed tests will be provided to the RAMI task group as specified in the statement of work.

A.3.12.2 Reliability Tests

Tests specifically formulated for obtaining reliability information will be designed as reliability tests. Such tests will be conducted when a clear necessity for the data is indicated and data from completed, existing, or planned tests are believed to be inadequate. The following types of tests will be considered.

A.3.12.2.1 Parameter or Distribution Evaluation

Parameter or distribution evaluation tests will be conducted to determine the numerical value of a parameter (failure rate, mean time to repair, life, etc.) or to determine the mathematical nature of a failure or repair distribution (normal, exponential, Weibull, etc.) for a particular device. In certain circumstances, both parameter and distribution information may be required. For example, unit-to-unit variability in material properties, dimensions, duty cycle, handling, environmental time histories, and other areas may dictate the need for a sufficient sample size to verify operational reliability characteristics.

A.3.12.2.2 Environmental Sensitivity

Environmental sensitivity tests will be performed to determine the effect of various environmental stresses on the device undergoing test. Such tests differ from the usual environmental and qualification tests when accelerated time or stress methods, or both, are used. The purpose of environmental sensitivity tests is to determine the boundaries of operation when earlier tests have not incorporated various environmental conditions subsequently deemed to be significant.

A.3.12.2.3 Demonstration

Demonstration tests will be conducted to verify that a quantitative reliability requirement has been achieved. When demonstration tests are formulated, the test descriptions shall include formal decision criteria, definition of failure, provisions for voiding the test, and quantitative indication of hypothesis risks (i.e., probabilities associated with making incorrect decisions).

Tests, other than those specified, may be recommended by a subcontractor. The specification of tests by the RAMI task does not relieve the subcontractor of responsibility for ensuring the reliability of the component systems covered by the contract.

A.3.12.3 Test Report

A test report shall be prepared for each test and shall contain the following information:

- Title page
- Table of contents
- Summary
- Objective of test
- Equipment tested
- Test facilities and equipment
- Test procedures
- Test data
- Certification of test results
- Test evaluation
- Conclusions and recommendations

A.3.13 DATA COLLECTION AND TREND ANALYSES

Reliability data may be derived from data-collection programs, analyses of operational and test experience, engineering judgment, and Bayesian analysis. Provisions will be made for the collection, analyses, updating, storage, and efficient dissemination of such information for use in the design of the component system.

A.3.14 CRITICAL ITEMS

Critical items are items whose failure could affect significantly the ability of a component system to perform its function effectively or safely. The critical items list can identify all components that (1) perform critical functions, (2) are reliability sensitive, (3) have long procurement times and limited life, (4) require formal statistical qualification, and (5) are high-cost items. The critical items list will be prepared and maintained throughout the component development program for the system. QA programs, special reliability studies, special maintenance and handling considerations, and reliability improvement programs shall be implemented for critical items as necessary to ensure that each item is acceptable for its intended application.

The identification of items in the component system design believed to be critical from the standpoint of reliability or availability is an excellent way to bring the importance of reliability matters into central focus. The earliest identification may be purely qualitative, perhaps derived from the FMEA. The list is periodically updated as the design progresses, as test results become available, and as further reliability studies are performed. A critical items list is a valuable management tool allowing management to deal with the most important reliability problems. The list simply reflects the state of knowledge at a given time. It is one of the least expensive reliability tasks in the project's lifetime.

A.3.15 PARTS AND MATERIALS SELECTION PROGRAM

The parts and materials selection program will ensure that the piece parts, materials, and components selected in the design process enable the component system to meet the established requirements. It also will minimize the number and types of different items used in the system. This program is particularly important in controlling critical items and maintaining standardized piece parts and designs.

The components facility design requirements, system design documents, or E-SPEC will establish criteria to control the selection and application of parts and material. The selection process should include

design analysis, reliability-experience review, failure analysis, screening, cost-effectiveness studies, and an application review and approval procedure. A controlled parts and material list will be prepared and implemented so that no drawing, specification, or other design definition document may contain or use any part of material not incorporated on the list. Furthermore, a continuous effort shall be pursued to standardize the design and manufacture of component system equipment.

A.3.16 DESIGN REVIEWS

Design reviews are conducted to assess the adequacy of the design with respect to criteria and requirements and to ensure that no deficiencies exist that could adversely affect safety, performance, or RAMI. The reviews should be comprehensive and critical of all pertinent aspects of systems design. Formal design reviews are planned and scheduled as an integral part of the major design review and identified in the RAMI program plan. Each design review and the necessary follow-up actions and closeouts will be documented in a report. Other mechanisms of the review, including attendees, review checklists notification, and other requirements of applicable QA program requirements documents, will be employed. When practicalable, design reviews should be scheduled and held during conceptual, intermediate, and final stages of system design. Equipment-system RAMI will be addressed in all design reviews.

Appendix B

GENERAL BIBLIOGRAPHY

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