SSCL-369

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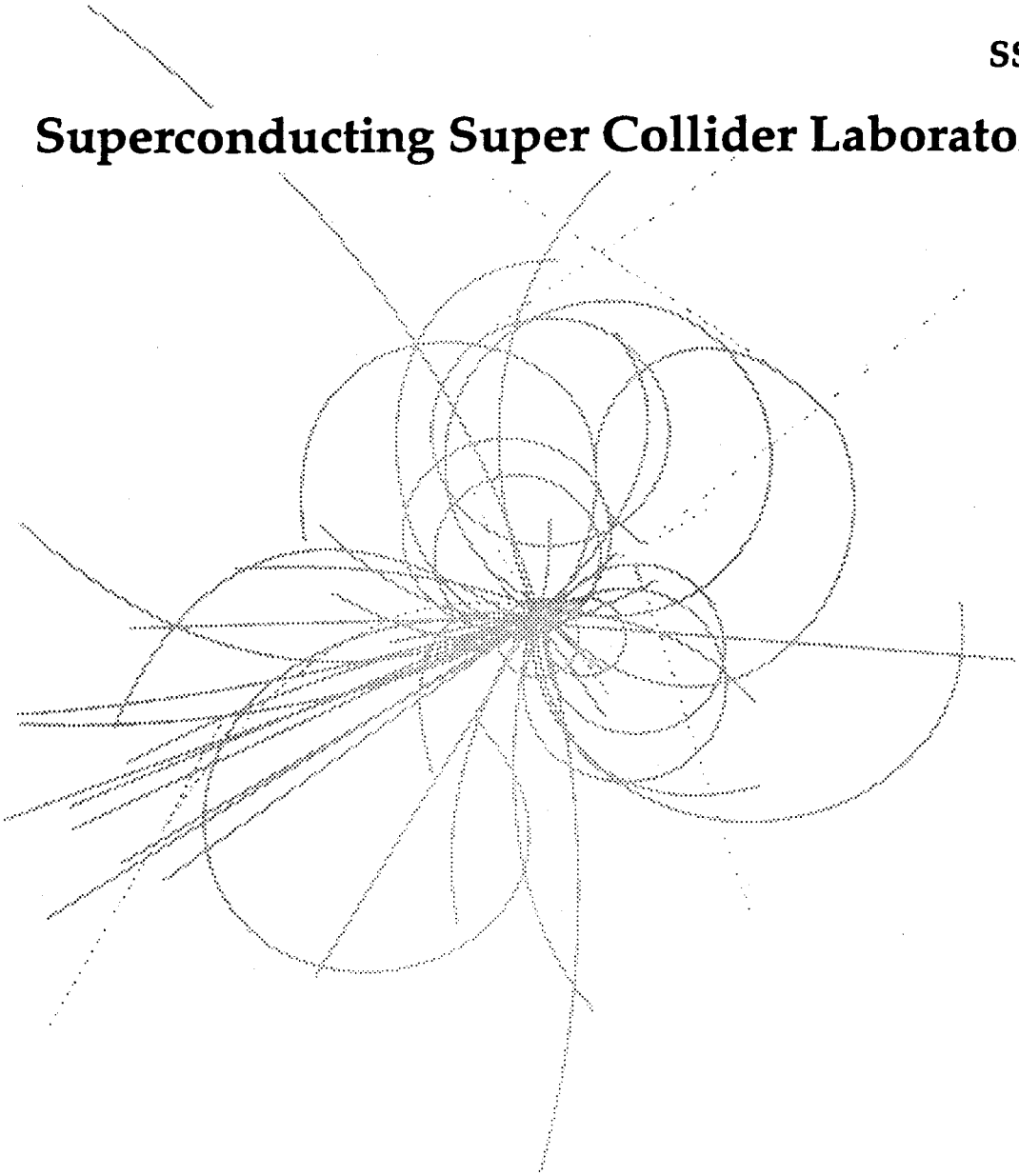
Superconducting Super Collider Laboratory



Designing Superconducting Magnets for Reliability and Availability

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March 1991

To be published in Supercollider 3, Plenum Press, New York

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March 1991

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*Presented at the 1991 International Industrial Symposium on the Super Collider, Atlanta, Georgia, March 13–15, 1991.

†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

INTRODUCTION

The Superconducting Super Collider Laboratory (SSCL) Conceptual Design Report (March 1986) sets the availability goal for the accelerator at 80%. The apportionment of the availability goal to the accelerator subsystems, and from the subsystems down to the major sub-subsystems such as the Collider Dipole Magnets (CDMs), is performed in the Reliability Allocation Analysis.

From the present Reliability Allocation Analysis, the Collider has an 82.4% availability, which further allocates an 88.2% availability goal for the magnets and interconnects. It can be shown that each CDM will have an availability of 99.99954%, which correlates to a 6305 Years Mean-Time-Between-Failure (MTBF) goal. This MTBF is based on the 10.5 Days Mean-Time-To-Repair (MTTR), which is defined in the Availability Analysis. From the availability requirement, the scheduled up-time, and the unscheduled down-time, it follows that an average of 1.3 CDMs can fail per year during the scheduled up-time.

As a result of the availability analysis, it is evident that the reliability goal for the CDM is an enormous technical challenge. The available data from national laboratories (e.g., Fermilab, Brookhaven, and Lawrence Berkeley) and from international accelerators provide information on design features to be avoided. However, the SSCL CDM design is differs to an extent that little confidence is obtained from analysis of historical data. The conventional statistical approach to reliability achievement and verification is not economically feasible due to the cost and time that would be required and the program delay that would result if the test failed.

The product integrity-based approach was proven effective by the aerospace industry and provides a systematic approach to reliability assurance suitable for SSC magnets. The following discussion is fairly specific to the CDM, but the same methodology is presently planned for the Collider Quadrupole, High Energy Booster Magnets and other special superconducting magnets.

INTEGRITY

At the Magnet Systems Division of the SSCL, the reliability program is based on the Integrity Methodology, a systematic, integrated, closed loop of reliability tasks performed in concert with the design/development/production tasks to ensure that the integrity built into the final product is compatible with lifetime reliability requirements. Figure 1 shows the basic order in which the tasks are performed and how the tasks relate to one another. The integrity approach includes a Failure Modes Effects and Criticality Analysis (FMECA), a Durability Analysis, a Test Program, a Failure Reporting Analysis and Corrective Action System (FRACAS), and a Maintainability/Prognostics task.

The emphasis of the integrity program is on identifying potential areas of significant problems and devising a scheme to work on the issues in a prioritized manner. From the availability allocation it was evident that the CDM would provide the best return for the effort. Reasons include the large number of CDMs (8460 units), the minimal experience building these magnets, the high amount of cross application to the other magnets to be studied, and the 25-year life requirement with a total of 33.5 failures permitted.

Conventional reliability programs are suitable for equipment with a permissible number of failures similar to a reference system that is available for comparison. This approach is usually started with an allocation and prediction using "same as" equipment, "similar to" hardware, mechanical handbooks, and electrical handbooks. The conventional approach may not include a FMECA, but it would usually include a FRACAS initiated at the qualification test. Unfortunately, many conventional reliability programs end with the

approval of the required data items and the approved qualification report, with no assurance that the reliability provisions are implemented in production.

FMECA

The primary intent of the FMECA is to identify critical items and place them in a prioritized list. The critical item list is the starting point for the durability analysis. The FMECA is designed to identify all possible failure modes, the actions required to eliminate or control the risk, the failure detection method for each failure mode, the compensating provisions, and the fault isolation provisions. To accurately obtain this goal, the FMECA requires a closed loop review process, as shown in Figure 2. Such a process is being used at the Magnet System Division of the SSCL. The document is reviewed not only by Magnet Design Engineering but by other departments as well, including Quality Assurance and Test and Manufacturing. Also, due to division overlaps it was important that the Accelerator and Physics Divisions reviewed the FMECA. The best way to get strong support is to have the division head support the review. Due to inter-department and inter-division effects, success of the effort is strongly dependent on division head support of the review and action item assignment. The review of the FMECA is a tedious and time-consuming process, but it is absolutely imperative in order to close out any open issues raised in the FMECA.

The FMECA Worksheet, Table 1, consists of 12 fields, each of which was specifically defined to permit consistency within each field and within the document. The fields include the item name, item number, failure mode, failure cause, item/component effect, magnet effect, collider end effect, failure detection method, failure rate, severity class, remarks, and failure prevention. Each field is self-explanatory from its title. Note that the failure effect was reviewed at the level of the component which failed, then at the magnet level, and finally at the collider level.

The CDM FMECA analyzed 73 items and identified 181 possible failure modes with 488 failure causes. Forty-seven failure modes were classified as critical (defined as having potential to cause severe injury, radiation exposure, or major collider damage which will result in extended system down-time). No catastrophic failure modes (involving loss of life or collider) have been identified by the FMECA. Again, all the FMECA goals must be met in order to increase the level of confidence for the CDM.

DURABILITY

Once the preliminary FMECA is in the initial review cycle, the Durability Analysis is the next effort to be performed. The Durability Analysis initially takes each critical component identified in the FMECA and examines all the steps required to go from a drawing to an end item operational in the collider tunnel.

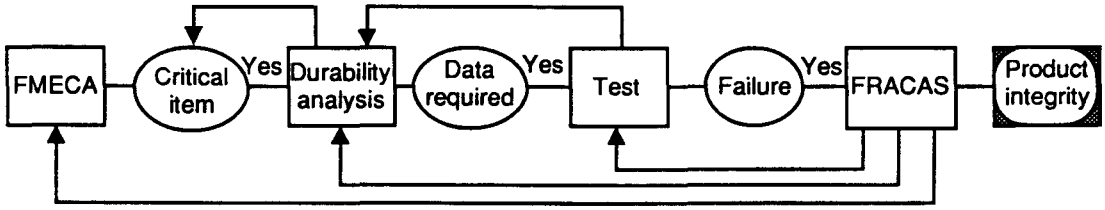

Figure 1. Integrity Reliability Tasks.

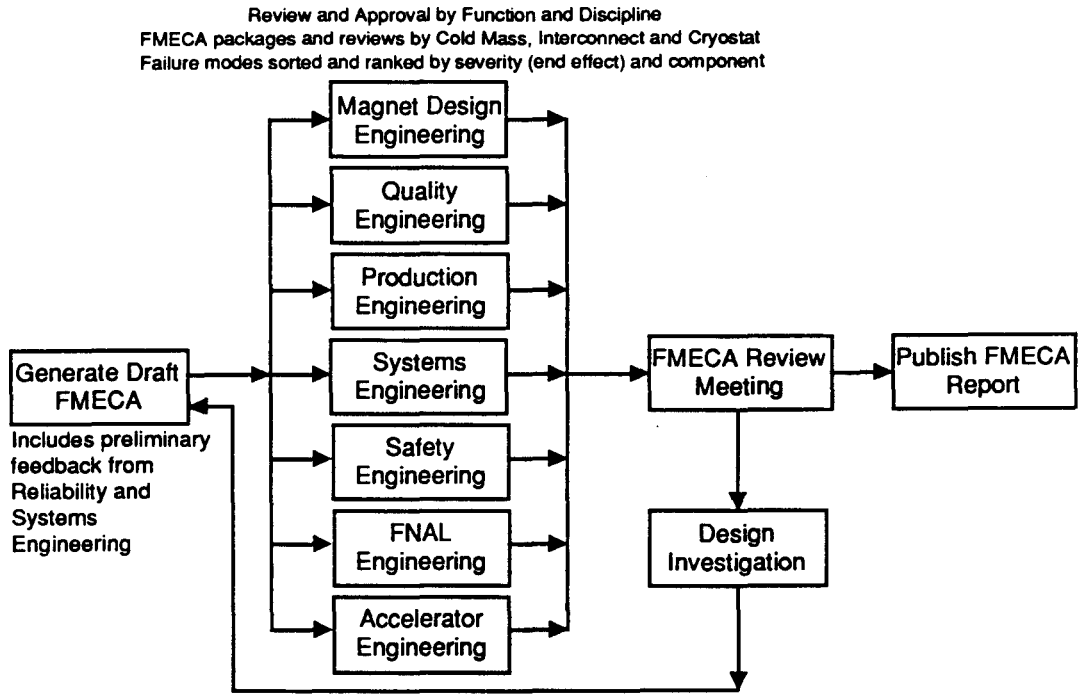

Figure 2. FMECA Review Process.

Table 1. CDM FMECA Worksheet.

ITEM NAME	ITEM NO.	FAILURE MODE	FAILURE CAUSES	ITEM EFFECT	MAGNET EFFECT	COLLIDER EFFECT	DETECTION METHOD	FAILURE RATE	SEVERITY CLASS	REMARKS	FAILURE PREVENTION

The intent of the analysis is to ensure that the design/development process has properly analyzed each part for life-determining stress levels, has selected materials with characteristics compatible with reliability and life requirements, and has developed manufacturing methods and controls consistent with material limitations and process variations. Once this effort is complete, quality control procedures can be expected to ensure production of reliable magnets. Table 2 shows the basic form used to document this analysis. The durability worksheet is composed of six fields: Environment, Item, Level, Specification, Method/Vendor Margin, and Method/SSCL Margin.

The Environment field includes subtopics such as manufacturing, test, packaging and handling, transportation, storage, installation, operation, and maintenance. The Item field includes topics such as temperature, humidity, stress, vibration, shock, magnetic cycles, thermal cycles, and quenches. The Level field allows a cursory look at the worksheet to quickly identify problem areas. The Level field may be 1) Acceptable, 2) Marginal, or 3) Unacceptable. Any Level 3 is highlighted on the worksheet for ease of identification. The Specification field is used to identify the requirement and where it is defined. The Method/Vendor Margin field provides room for a brief written explanation of the vendor's analysis, methodology, and margin. The Method/SSCL Margin field provides a place to state the SSCL's analysis, methodology, and margin for that specific item.

The manufacturing environments are unique for each part under analysis. To properly address the various manufacturing environments, the field permits sub-environments under the main manufacturing environment. Some examples of the manufacturing sub-environments include forming, pressing, welding. and inspections. The unique details studied during the manufacturing phase permit a strong understanding of the item and its characteristics to be obtained, deviations from requirements to be identified, and control processes to be specified, implemented and verified as effective.

Results of the Durability Analysis and the FMECA will help identify and concentrate efforts on the highest risk items first; lower-risk cases can be addressed later. Once the Durability Analysis is completed on a component/item, the level of confidence that integrity can be achieved and maintained over the life of the item is significantly increased. Information acquired on the item under analysis is reflected back into the FMECA for completeness and technical accuracy. If the Durability Analysis determines an unacceptable unknown, then a test may be defined to reduce the risk to an acceptable level.

TEST

Various tests are conducted simultaneous with the above analyses. Unlike conventional reliability programs, which do little or no tracking or failure analysis until the formal qualification process, the integrity approach uses as much of the development testing as possible to help find new modes and causes of failure and to take corrective actions. This approach allows the risk to be reduced as the program moves toward production by validating hardware performance and eliminating in a timely manner any potential design weaknesses discovered. Testing includes CDM component/item tests, CDM acceptance testing during assembly, performance testing, and development accelerated- life testing. The life test program, coupled with the product integrity design-for-reliability approach, will provide magnets that meet SSCL requirements.

Durability testing of completed magnets is planned for the immediate future. A full-length, 40 mm CDM is presently scheduled for extended cycle testing. The test goal is 28 quenches, 14 thermal cycles, and an equivalent of 7,400 magnetic cycles, as well as experience in life-testing a CDM. The test will make use of acceleration factors including operation 10% over the normal magnetic field and electrical power ramp rates up to 25 times the normal value of 4 A/sec. Life-test of a 5(mm CDM built to the Accelerator Surface String Test (ASST) configuration is planned.

Table 2. Durability Analysis Worksheet.

PART NUMBER DESCRIPTION	XX-XXXXXX ASSEMBLY		AVERAGE ENVIRONMENT 253-310 K 10-98% RH VIBRATION SHOCK 2g/1g/1g	LEVEL CODES 1-ACCEPTABLE 2-MARGINAL 3-UNACCEPTABLE INVESTIGATION REQUIRED	
ENVIRONMENT	ITEM	LEVEL	SPECIFICATION	METHOD/VENDOR MARGIN	METHOD/SSCL MARGIN
MAGNET					
PACKAGE/HAND	AMBIENT TEMPERATURE HUMIDITY SHOCK VIBRATION AIRBORNE PARTICULATES REQUIREMENTS PROCEDURES				
TRANSPORTATION	AMBIENT TEMPERATURE HUMIDITY SHOCK VIBRATION				
INSTALL	AMBIENT TEMPERATURE HUMIDITY AIRBORNE PARTICULATES SHOCK VIBRATION				
OPERATION	MAGNETIC CYCLES QUENCH CYCLES THERMAL CYCLES AMBIENT TEMPERATURE HUMIDITY SHOCK VIBRATION				
MAINTENANCE	AMBIENT TEMPERATURE HUMIDITY AIRBORNE PARTICULATES SHOCK VIBRATION				

Component testing plays an important role by allowing individual components to be evaluated prior to being included in the magnet design. Component testing provides early feedback during the design process and permits development magnets to include "proven reliable" items. Component testing to date includes 40 mm re-entrant posts, electrical bus expansion loops, and aluminum-to-steel cryogen transition joints. Component testing presently planned includes 50 mm re-entrant posts, cryogen bellows, electrical insulation, cable splices, and instrumentation connections. Any component determined from the durability or failure modes analysis to require individual testing is expected to be tested during the magnet development phase.

The lessons learned from these tests provide the insight needed for long-term magnet production. Failures during manufacturing also provide insight as to which present tests are inadequate and which tests if any need to be incorporated into the quality inspections. Also, by examining development assembly problems, the design engineering and production groups can iterate the design or obtain understanding of the design margin.

This explanation of how reliability engineering approaches testing while functioning under the integrity methodology makes it plain that it involves not only the design engineering group, but the quality assurance, production, and test engineering groups as well. Constant communication between these groups is imperative to making the system a positive entity.

FRACAS

To ensure that the test program results are fed back into the design, FRACAS is applied to all testing being performed. FRACAS is a closed-loop discrepancy reporting

system that collects/analyzes data and ensures that corrective action is taken when discrepancies are reported on procured/fabricated items.

FRACAS covers discrepancies or non-conformance during the following tests or operations: 1) development test, 2) functional acceptance test, 3) reliability test, 4) systems and integration test, 5) verification test, 6) testing and/or repair associated with hardware returned from field usage, 7) tests performed at vendors, other labs, and the SSCL test lab facilities, 8) SSCL operations, 9) manufacturing non-conformance, and 10) other discrepancies identified in tooling, manufacturing procedures, or other areas directly impacting quality of the end item.

Figure 3 presents the basic steps of FRACAS. Notification of the failure by the receipt of the data report leads to convening of the Failure Review Board (FRB) "As Required" to discuss the failure and the proposed failure analysis plan or the proposed corrective action. The failure analysis plan is assigned to a cognizant engineer. Once the cause of the failure has been determined, corrective action is defined, agreed upon, implemented, and verified.

For Class 1 failures—defined as any affecting form, fit, function, reliability,or safety—initial failure notification is required within 24 hours of discovery by either the subcontractor, the national laboratories or the SSCL. Once notified, the FRACAS coordinator provides failure notification simultaneously to the product manager, Engineering, and Production and Quality Assurance. The product manager has the authority to initiate an investigation of the discrepancy and analysis of the data and to take any repair and/or corrective action required as a result of the discrepancy. This includes involvement of the Failure Review Board.

Within five working days of the initial failure notification, the responsible party is required to provide any additional data from the original notification and a plan to perform any necessary failure analysis. Within 30 days the reporting organization is required to provide the completed failure investigation data, with a determination of cause, suggested corrective action, and possible verification method. Note that the Failure Review Board has final approval of the failure report and corrective action proposal.

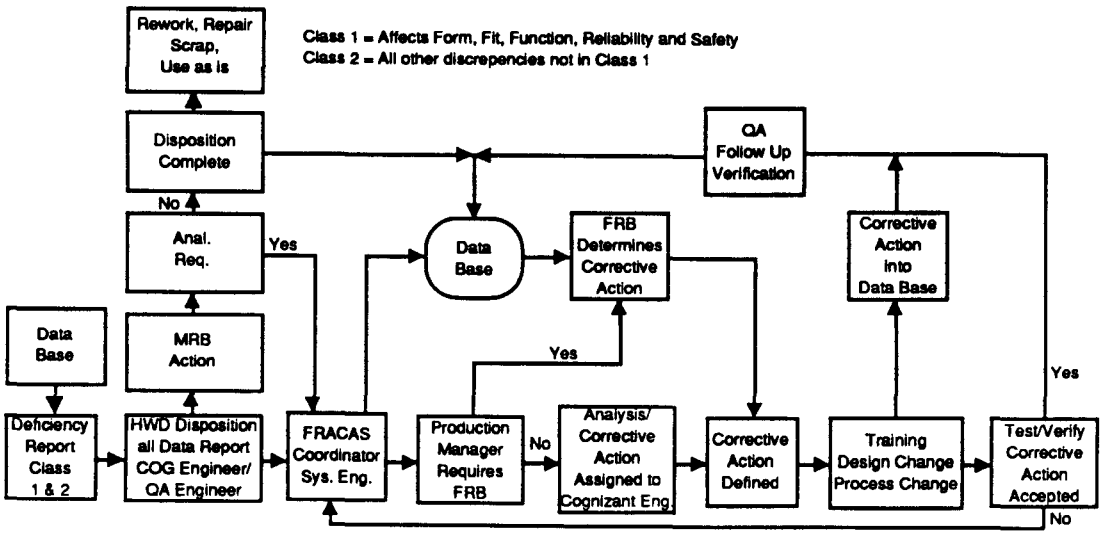

Figure 3. FRACAS Flowchart at SSCL.

Reliability Engineering is responsible for maintaining the FRACAS data base, which includes all the magnet Class 1 failure analysis data and can link to the Class 2 failure data and performance test data loaded into the MSD main computer. The FRACAS data base provides trend analysis capability, input for status meetings, and support for the monthly FRACAS Summary Report. The last two items are provided to and supported by the head of Magnet System Division. Reliability Engineering is also responsible for maintaining a record of data accumulated through FRACAS to update the FMECA.

MAINTAINABILITY

The program described above will provide the lowest number of magnet failures possible within the cost and schedule constraints of the overall SSCL program. However, it is not yet clear that "the lowest number possible" is less than the maximum number allowed by the availability allocation. Therefore, the use of prognostics may become essential to high availability achievement. Prognostics is defined as the ability to predict impending failures and to correct the situation before failure occurs. Prognostics depends on the ability to monitor the health of the magnet in operation and to track parameter trends toward failure conditions. Prognostics may be enhanced by the capability to relate failures and drifting parameters to production and/or operational variables such as material quality imperfections, acceptance test parameter values, or excessive-life consuming events (e.g., quenches and temperature cycles).

Such a capability could require an enormous database and widespread monitoring/recording system. Techniques to identify poor or weak magnets during operation must be addressed and investigated during the magnet development phase. Data obtained during the magnet testing constitute the initial step in determining the means and capability of a prognostic system. If accurate prognostics is feasible, it becomes possible to have more than the allocated number of failures occur.

SUMMARY

This report presents reasons why a logical system approach, the integrity methodology, was chosen over a classical approach to reliability achievement. The primary reason for this selection is the design of the CDM to be failure-free for its 25-year life. The paper reviewed each major reliability task of the integrity approach and explained how each task interfaces with other applicable tasks. Finally, the importance of prognostics was discused as a possible maintenance approach to optimize the use of down-time, thus increasing the availability of the SSC.

Reliable magnet achievement is in the hands of those who actually design, test, and deliver the magnets. Accomplishment of reliability program tasks merely serves as a tool for identifying issues—often interdisciplinary or inter-organizational in nature—that could preclude reliability achievement. Timely management action to resolve these issues is a fundamental requirement for program success.

ACKNOWLEDGMENTS

Thanks go to Kirby Dixon, SSCL and Lockheed Systems Engineer, lead reliability engineer, who performed the availability analysis and provided technical support.

Also to James Franciscovich, SSCL and Lockheed Systems Engineer, Systems Engineering Group Manager, who provided technical input and document review.

And to Jim Potter, SSCL and Lockheed Systems Engineer, lead reliability engineer, who provided technical support and document review.