SEMI E10-0304[E]
SPECIFICATION FOR DEFINITION AND MEASUREMENT OF EQUIPMENT RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM)

This specification was technically approved by the Global Metrics Committee and is the direct responsibility of the North American Metrics Committee. Current edition approved by the North American Regional Standards Committee on October 15, 2003. Initially available at www.semi.org February 2004; to be published March 2004. Originally published in 1986; previously published July 2001.

[E] This standard was editorially modified in February 2004 to include changes omitted from the previous edition. Changes were made to Table 1, Table R1-3, and Section R1-7.

1 Purpose

1.1 This document establishes a common basis for communication between users and suppliers of semiconductor manufacturing equipment by providing standards for measuring RAM performance of that equipment in a manufacturing environment.

2 Scope

2.1 The document defines six basic equipment states into which all equipment conditions and periods of time must fall. The equipment states are determined by functional issues, independent of who performs the function. The measurement of equipment reliability in this specification concentrates on the relationship of equipment failures to equipment usage, rather than the relationship of failures to total elapsed time.

2.2 Section 5 (Equipment States) defines how equipment time is categorized. Section 6 (RAM Measurement) defines formulas for measurement of equipment performance. Section 7 (Uncertainty Measurement) gives additional methods for evaluating the statistical significance of calculated performance metrics.

2.3 Effective application of this specification requires that equipment performance (RAM) be tracked with regard to time and/or equipment cycles. Automated tracking of equipment states is not within the scope of this specification, but is covered by SEMI E58. Clear and effective communication among users and suppliers promotes continuous improvement in equipment performance.

2.4 The RAM indices in this specification may be applied directly to non-cluster tools at the whole equipment and sub-system levels. The RAM indices may be applied at the sub-system level (e.g., process module) for multi-path cluster tools.

NOTICE: This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory or other limitations prior to use.

3 Referenced Standards

3.1 *SEMI Standards*

SEMI E58 — Automated Reliability, Availability, and Maintainability Standard (ARAMS)

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

4 Terminology

4.1 *Definitions*

4.1.1 *availability* — the probability that the equipment will be in a condition to perform its intended function when required.

4.1.2 *cluster tool* — a manufacturing system made up of integrated processing modules mechanically linked together (the modules may or may not come from the same supplier).

4.1.2.1 *single path cluster tool* — a cluster tool with only one process flow path (as used).

4.1.2.2 *multi-path cluster tool* — a cluster tool with more than one independent process flow path (e.g., multiple load ports/load-locks, multiple process chambers of the same type) and used as such.

4.1.3 *cycle* — one complete operational sequence (including unit load and unload) of processing, manufacturing, or testing steps for an equipment system or subsystem. In single unit processing systems, the number of cycles equals the number of units processed. In batch systems, the number of cycles equals the number of batches processed.

4.1.4 *downtime (DT)* — the time when the equipment is not in a condition, or is not available, to perform its intended function. It does not include any portion of non-scheduled time.

4.1.5 *downtime event* — a detectable occurrence significant to the equipment that causes the equipment to go from an uptime state to either a scheduled or an unscheduled downtime state.

4.1.6 *failure* — any unscheduled downtime event that changes the equipment to a condition where it cannot perform its intended function. Any part failure, software or process recipe problem, facility or utility supply malfunction, or human error could cause the failure.

NOTE 1: It is important to categorize and qualify failures in ways that facilitate the resolution of problems and improve overall equipment performance. Use of this specification requires agreement between supplier and user on categorizing failures.

4.1.7 *equipment-related failure* — any unplanned event that changes the equipment to a condition where it cannot perform its intended function solely caused by the equipment.

4.1.8 *host* — the intelligent system that communicates with the equipment, acts as a supervisory agent, and represents the factory and the user to the equipment.

4.1.9 *intended function* — a manufacturing function that the equipment was built to perform. This includes transport functions for transport equipment and measurement functions for metrology equipment, as well as process functions such as physical vapor deposition and wire bonding. Complex equipment may have more than one intended function.

4.1.10 *maintainability* — the probability that the equipment will be retained in, or restored to, a condition where it can perform its intended function within a specified period of time.

4.1.11 *maintenance* — the act of sustaining equipment in or restoring it to a condition to perform its intended function. In this document, maintenance refers to function, not organization; it includes adjustments, change of consumables, software upgrades, repair, preventive maintenance, etc., no matter who performs the task.

4.1.12 *manufacturing time* — the sum of productive time and standby time.

4.1.13 *non-scheduled time* — the time when the equipment is not scheduled to be utilized in production.

4.1.14 *operations time (oper-time)* — total time minus non-scheduled time.

4.1.15 *operator* — any person who communicates locally with the equipment through the equipment's control panel.

4.1.16 *product* — units produced during productive time (see unit).

4.1.17 *ramp-down* — the portion of a maintenance procedure required to prepare the equipment for hands-on work. It includes purging, cool-down, warm-up, software backup, storing dynamic values (e.g., parameters, recipes), etc. Ramp-down is only included in scheduled and unscheduled downtime.

4.1.18 *ramp-up* — the portion of a maintenance procedure required, after the hands-on work is completed, to return the equipment to a condition where it can perform its intended function. It includes pump down, warm-up, stabilization periods, initialization routines, software load, restoring dynamic values (e.g., parameters, recipes), control system reboot, etc. It does not include equipment or process test time. Ramp-up is only included in scheduled and unscheduled downtime.

4.1.19 *reliability* — the probability that the equipment will perform its intended function, within stated conditions, for a specified period of time

4.1.20 *shutdown* — the time required to put the equipment in a safe condition when entering a non-scheduled state. It includes any procedures necessary to reach a safe condition. Shutdown is only included in non-scheduled time.

4.1.21 *specification (equipment operation)* — the documented set of intended functions within stated conditions for equipment operation as agreed upon between user and supplier.

4.1.22 *start-up* — the time required for equipment to achieve a condition where it can perform its intended function, when leaving a non-scheduled state. It includes pump down, warm-up, cool-down, stabilization periods, initialization routines, software load, restoring dynamic values (e.g., parameters, recipes), control system reboot, etc. Start-up is only included in non-scheduled time.

4.1.23 *support tool* — a tool that, although not part of a piece of equipment, is required by and becomes integral with it during the course of normal operation (e.g., cassettes, wafer carriers, probe cards, computerized controllers/monitors).

4.1.24 *total time* — all time (at the rate of 24 hrs/day, 7 days/week) during the period being measured. In order to have a valid representation of total time, all six basic equipment states must be accounted for and tracked accurately.

4.1.25 *training (off-line)* — the instruction of personnel in the operation and/or maintenance of equipment done outside of operations time. Off-line training is only included in non-scheduled time.

4.1.26 *training (on-the-job)* — the instruction of personnel in the operation and/or maintenance of equipment done during the course of normal work functions. On-the-job training typically does not interrupt operation or maintenance activities and can therefore be included in any equipment state (except standby and non-scheduled) without special categorization.

4.1.27 *unit* — any wafer, substrate, die, packaged die, or piece part thereof.

4.1.28 *uptime* — the time when the equipment is in a condition to perform its intended function. It includes productive, standby, and engineering time, and does not include any portion of non-scheduled time.

4.1.29 *user* — any entity interacting with the equipment, either locally as an operator or remotely via the host. From the equipment's view point, both the operator and the host represent the user.

4.1.30 *utilization* — the percent of time the equipment is performing its intended function during a specified time period.

4.1.31 *verification run* — a single cycle of the equipment (using units or no units) used to establish that it is performing its intended function within specifications.

5 Equipment States

5.1 To clearly measure equipment performance (RAM), this document defines six basic equipment states into which all equipment conditions and periods of time must fall.

5.2 The equipment states are determined by function, not by organization. Any given maintenance procedure, for example, is classified the same way no matter who performs it, an operator, a production technician, a maintenance technician, or a process engineer.

5.3 Figure 1 is a stack chart of the six basic equipment states. These basic equipment states can be divided into as many sub-states as are required to achieve the equipment tracking resolution that a manufacturing operation desires. SEMI E10 makes no attempt to list all possible sub-states, but does give some examples for guidance.

5.4 Key blocks of time associated with the basic states and example substates are given in Figure 2. These blocks of time are used in the RAM equations given later in this document. The blocks of time associated with the basic states and example substates are described in the following sections.

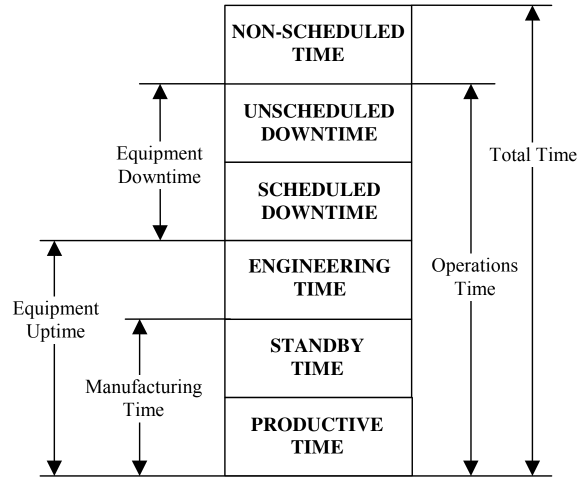


Figure 1
Equipment States Stack Chart

5.5 *PRODUCTIVE STATE* — The time (productive time) when the equipment is performing its intended function. The productive state includes:

- Regular production (including loading and unloading of units),
- Work for third parties,
- Rework, and
- Engineering runs done in conjunction with production units (e.g., split lots and new applications).

5.6 *STANDBY STATE* — The time (standby time), other than non-scheduled time, when the equipment is in a condition to perform its intended function, chemicals and facilities are available, but it is not operated. The standby state includes:

- No operator available (including breaks, lunches, and meetings),
- No units available (including no units due to lack of available support equipment, such as metrology tools),
- No support tools (e.g., cassettes, wafer carriers, probe cards), and
- No input from external automation systems (i.e., host).

5.7 *ENGINEERING STATE* — The time (engineering time) when the equipment is in a condition to perform its intended function (no equipment or process problems exist), but is operated to conduct engineering experiments. The engineering state includes:

- Process engineering (e.g., process characterization),
- Equipment engineering (e.g., equipment evaluation), and
- Software engineering (e.g., software qualification).

5.8 *SCHEDULED DOWNTIME STATE* — The time (scheduled downtime) when the equipment is not available to perform its intended function due to planned downtime events. The scheduled downtime state includes:

- Maintenance delay (maint-delay),
- Production test,
- Preventive maintenance,
- Change of consumables/chemicals,
- Setup, and
- Facilities related (fac-rel).

5.8.1 *Maintenance Delay* — The time (maint-delay downtime) during which the equipment cannot perform its intended function because it is waiting for either user or supplier personnel or parts (including consumables/chemicals) associated with maintenance. Maintenance delay may also be due to an administrative decision to leave the equipment down and postpone maintenance.

5.8.1.1 Maintenance delays may occur at any point in the maintenance process. These maintenance delay downtimes must be tracked separately from maintenance time. Delay downtime is included in time off-line, but not in time to repair (see Sections 6.3 and 6.4 Equipment Availability and Maintainability).

5.8.2 *Production Test* — The time (production test downtime) for the planned interruption of equipment availability for evaluation of units, as defined in the specifications of equipment operation, to confirm that the equipment is performing its intended function within specifications. It does not include testing that can be done in parallel with, or transparent to, the running of production, nor does it include any testing done following a preventive maintenance, setup, or repair procedure.

5.8.3 *Preventive Maintenance* — The sum of the times (preventive maintenance downtimes) for:

- Preventive action: A predefined maintenance procedure (including equipment ramp-down and ramp-up), at scheduled intervals, designed to reduce the likelihood of equipment failure during operation. Scheduled intervals may be based upon time, equipment cycles, or equipment conditions.
- Equipment test: The operation of equipment to demonstrate equipment functionality; (e.g., system reaches base pressure, wafers transfer without problem, gas flow is correct, plasma ignites, source reaches specified power).
- Verification run: The processing and evaluation of units after preventive action to establish that the equipment is performing its intended function within specifications.

NOTE 2: Equipment suppliers are responsible for specifying a preventive maintenance program to achieve a predetermined equipment performance level. Users are obligated to identify any deviation from the recommended program if they expect the supplier to meet or improve that performance level.

5.8.4 *Change of Consumables/Chemicals* — The time (change of consumables/chemicals downtime) for the scheduled interruption of operation to replenish the raw materials of semiconductor processing. It includes changes of gas bottles, acids, targets, sources, etc., and any purging, cleaning, or flushing normally associated with those changes. It does not include delays in obtaining those consumables/chemicals.

5.8.5 *Setup* — The sum of the times (setup downtimes) for:

- Conversion: The time required to complete an equipment alteration necessary to accommodate a change in process, unit, package configuration, etc. (excluding modifications, rebuilds, and upgrades).
- Equipment test: The operation of equipment to demonstrate equipment functionality; (e.g., system reaches base pressure, wafers transfer without problem, gas flow is correct, plasma ignites, source reaches specified power).
- Verification run: The processing and evaluation of units after conversion to establish that equipment is performing its intended function within specifications.

NOTE 3: Equipment suppliers are responsible for providing procedures which achieve setup conversion and testing within predetermined specifications. Users are obligated to identify any deviation from the procedures if they expect the supplier to make setups fall within those specifications.

5.8.6 *Facilities Related* — The time (facilities-related downtime) when the equipment cannot perform its intended function solely as a result of out of specification facilities. Those facilities include:

- Environmental (e.g., temperature, humidity, vibration, particle count),
- House hookups (e.g., power, cooling water, house gases, exhaust, LN2), and

- Communications links with other equipment or host computers.

5.8.6.1 Any downtime created by the items listed above shall be included in facilities-related downtime. For example, if, as a result of a scheduled 15-minute power outage an otherwise unnecessary cryo pump regeneration is needed, all time required to return the equipment to a condition where it can perform its intended function is included in facilities-related downtime.

5.9 *UNSCHEDULED DOWNTIME STATE* — The time (unscheduled downtime) when the equipment is not in a condition to perform its intended function due to unplanned downtime events:

- Maintenance delay (maint-delay)
- Repair
- Change of consumables/chemicals
- Out-of-spec input
- Facilities related (fac-rel)

5.9.1 *Maintenance Delay* — The time (maint-delay downtime) during which the equipment cannot perform its intended function because it is waiting for either user or supplier personnel or parts (including consumables/chemicals) associated with maintenance. Maintenance delay may also be due to an administrative decision to leave the equipment down and postpone maintenance.

5.9.1.1 Maintenance delays may occur at any point in the maintenance process. These maintenance delay downtimes should be tracked separately from maintenance time. Delay downtime is included in time off-line, but not in maintenance time (see Sections 6.3 and 6.4 Equipment Availability and Maintainability).

5.9.2 *Repair* — The sum of the times (repair downtimes) for:

- Diagnosis: The procedure of identifying the source of an equipment problem or failure.
- Corrective action: The maintenance procedure (including equipment ramp-down and ramp-up, re-booting, resetting, recycling, restarting, reverting to a previous software version, etc.) employed to address an equipment failure and return the equipment to a condition where it can perform its intended function.
- Equipment test: The operation of equipment to demonstrate equipment functionality (e.g., system reaches base pressure, wafers transfer without problem, gas flow is correct, plasma ignites, source reaches specified power).
- Verification run: The processing and evaluation of units after corrective action to establish that the equipment is performing its intended function within specifications.

5.9.3 *Change of Consumables/Chemicals* — The time (change of consumables/chemicals downtime) for the unscheduled interruption of operation to replenish the raw materials of semiconductor processing. It includes changes of gas bottles, acids, targets, sources, etc., and any purging, cleaning, or flushing normally associated with those changes. It does not include delays in obtaining these consumables/chemicals.

5.9.4 *Out-of-Spec Input* — The time (out-of-spec input downtime) when the equipment cannot perform its intended function solely as a result of problems created by out-of-specification or faulty inputs. Those inputs include:

- Support tools (e.g., warped cassettes or wafer carriers, faulty probe cards, reticles),
- Unit (e.g., upstream process problems, warped wafers, contaminated wafers, warped lead frames),
- Test data (e.g., metrology tool out of calibration, misread charts, erroneous data interpretation/entry), and
- Consumables/chemicals (e.g., contaminated acid, leaky target bond, degraded photo resist, degraded mold compound).

5.9.4.1 Any downtime created by the items listed above shall be included in out-of-specification input downtime. For example, if, as a result of an intermittent probe card short, a prober/tester system is put down for repair, all downtime incurred prior to identifying the problem is re-categorized as out-of-specification input downtime.

5.9.5 *Facilities Related* — The time (facilities-related downtime) when the equipment cannot perform its intended function solely as a result of out-of-specification facilities. Those facilities include:

- Environmental (e.g., temperature, humidity, vibration, particle count),
- House hookups (e.g., power, cooling water, house gases, exhaust, LN2), and
- Communications links with other equipment or host computers.

5.9.5.1 Any downtime created by the items listed above shall be included in facilities-related downtime. For example, if, as a result of an unscheduled 15-minute power outage, an otherwise unnecessary cryo pump regeneration is needed, all time required to return the equipment to a condition where it can perform its intended function is included in facilities-related downtime.

5.10 *NON-SCHEDULED STATE* — The time (non-scheduled time) when the equipment is not scheduled to be utilized in production, such as unworked shifts, weekends, and holidays (including shutdown and start-up).

5.10.1 If equipment is out of the production plan due to off-line training or an installation, modification, rebuild, or upgrade (hardware or software) that cannot be accommodated by the regular preventive maintenance schedule, its status is the non-scheduled state. This includes any qualification time required to bring the equipment to a condition where it can perform its intended function from one of these states.

5.10.2 Any maintenance done to equipment during these periods cannot be counted in the non-scheduled state, since all maintenance must fall into either scheduled or unscheduled downtime (this includes automatic maintenance routines such as a programmed cryo pump regeneration).

5.10.3 By the same convention, any production or engineering work done during these periods must fall into either productive or engineering time (this includes an unattended operation that may shut itself off "after hours").

6 RAM Measurement

6.1 Reliability, availability, and maintainability are measures of equipment performance which have been used widely in industry for decades. This section defines them for the semiconductor industry in a manner that is consistent with existing industrial standards. Along with the definitions for RAM are given indicators by which these measures can be quantified.

6.2 *EQUIPMENT RELIABILITY* — The probability that the equipment will perform its intended function, within stated conditions, for a specified period of time.

NOTE 4: Two different methods of measuring this are presented, productive time (Sections 6.2.1 and 6.2.2) and equipment cycles (Sections 6.2.3 and 6.2.4):

- Productive time only considers what happens while making units (useful for manufacturing operation purposes).
- Equipment cycles take into account the wear and tear created by every machine cycle during all equipment states (useful for equipment reliability purposes).

6.2.1 $MTBF_p$ — Mean (productive) time between failures; the average time the equipment performed its intended function between failures; productive time divided by the number of failures during that time. Only productive time is included in this calculation. Failures that occur when an attempt is made to change from any state to a productive state are included in this calculation. Using $MTBF_p$, therefore, requires that the user not only have the capability of capturing failure information, but also tracking and categorizing total time accurately.

$$MTBF_p = \frac{\textit{productive time}}{\textit{\# of failures that occur during productive time}}$$

6.2.2 $E\text{-}MTBF_p$ — Mean (productive) time between equipment-related failures; the average time the equipment performed its intended function between these equipment-related failures; productive time divided by the number of equipment-related failures during that time. Only productive time is included in this calculation. Equipment-related failures that occur when an attempt is made to change from any state to a productive state are included in this calculation. Using $E\text{-}MTBF_p$, therefore, requires that the user not only have the capability of capturing failure information, but also tracking and categorizing total time and the root causes of failures accurately.

$$E\text{–}MTBF_p = \frac{\textit{productive time}}{\textit{\# of equipment-related failures that occur during productive time}}$$

6.2.3 *MCBF* — Mean cycles between failures; the average number of equipment cycles between failures; total equipment cycles divided by the number of failures during those cycles. This calculation transcends equipment states to include all cycles that the system, or subsystem, being considered experiences. It does not require tracking equipment states, only equipment cycles and equipment failures.

$$MCBF = \frac{\textit{total equipment cycles}}{\textit{\# of failures}}$$

6.2.4 *E-MCBF* — Mean cycles between equipment-related failures; the average number of equipment cycles between these equipment-related failures; total equipment cycles divided by the number of equipment-related failures during those cycles. This calculation transcends equipment states to include all cycles that the system, or subsystem, being considered experiences. It does not require tracking equipment states, only equipment cycles and equipment-related failures and their root causes.

$$E\text{–}MCBF = \frac{\textit{total equipment cycles}}{\textit{\# of equipment-related failures}}$$

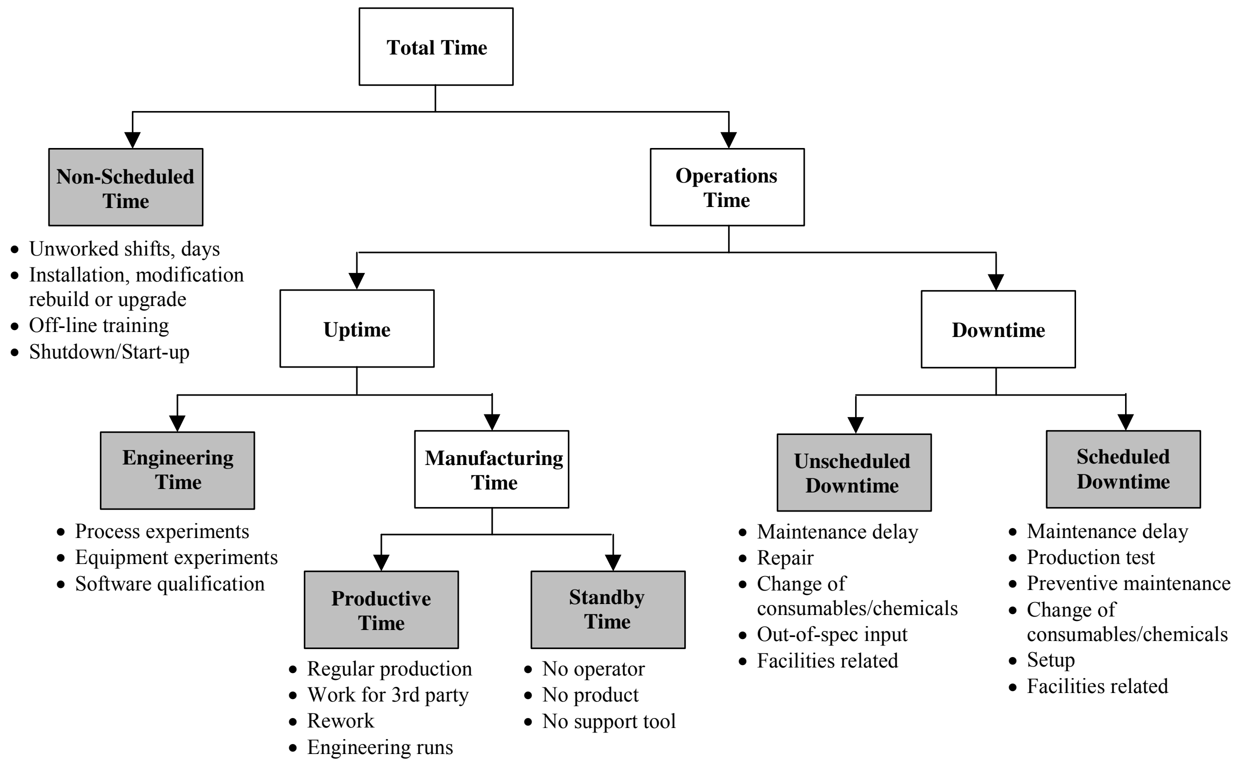


Figure 2
SEMI E10 Summary of Time

6.3 *EQUIPMENT AVAILABILITY* — The probability that the equipment will be in a condition to perform its intended function when required.

6.3.1 *Equipment Dependent Uptime* — The percent of time the equipment is in a condition to perform its intended function during the period of operations time minus the sum of all maintenance delay downtime, out-of-spec input downtime, and facilities-related downtime. This calculation is intended to reflect equipment reliability and maintainability based solely on equipment merit.

$$\textit{equipment dependent uptime (\%)} = \frac{\textit{equipment uptime} \times 100}{(\textit{oper-time} - (\textit{all maint-delay DT} + \textit{out-of-spec input DT} + \textit{fac-rel DT}))}$$

6.3.2 *Supplier Dependent Uptime* — The percent of time the equipment is in a condition to perform its intended function during the period of operations time minus the sum of user maintenance delay downtime, out-of-spec input downtime, and facilities-related downtime. This calculation subtracts only user maintenance delay downtime from the period, thereby taking into account supplier delays for parts and service. The intention is to provide an effective performance measurement for use in supplier service contracts.

$$\textit{supplier dependent uptime (\%)} = \frac{\textit{equipment uptime} \times 100}{(\textit{oper-time} - (\textit{user maint-delay DT} + \textit{out-of-spec input DT} + \textit{fac-rel DT}))}$$

6.3.3 *Operational Uptime* — The percent of time the equipment is in a condition to perform its intended function during the period of operations time. This calculation is intended to reflect overall operational performance for a piece of equipment.

$$\textit{operational uptime } (\%) = \frac{\textit{equipment uptime} \times 100}{\textit{operations time}}$$

6.4 *EQUIPMENT MAINTAINABILITY* — The probability that the equipment will be retained in, or restored to, a condition where it can perform its intended function within a specified period of time.

6.4.1 *MTTR* — Mean time to repair; the average time to correct a failure and return the equipment to a condition where it can perform its intended function; the sum of all repair time (elapsed time not necessarily total man hours) incurred during a specified time period (including equipment and process test time, but not including maintenance delay downtime), divided by the number of failures during that period.

$$MTTR = \frac{total\ repair\ time}{\#\, of\ \ failures}$$

6.4.2 *E-MTTR* — Mean time to repair equipment-related failures; the average time to correct an equipment-related failure and return the equipment to a condition where it can perform its intended function; the sum of all equipment-related failure repair time (elapsed time, not necessarily total man hours) incurred during a specified time period (including equipment and process test time, but not including maintenance delay downtime), divided by the number of equipment-related failures during that period.

$$E\text{–}MTTR = \frac{total\ repair\ time\ for\ equipment\text{-}related\ failures}{\#\ of\ equipment\text{-}related\ failures}$$

6.4.3 *MTOL* — Mean time off-line; the average time to maintain the equipment in or return the equipment to a condition where it can perform its intended function when downtime is incurred; the sum of all downtime (scheduled and unscheduled) during a specified time period, divided by the number of downtime events during that period.

$$MTOL = \frac{total\ equipment\ downtime}{\#\ \ of\ DT\ events}$$

6.4.4 *Equipment Dependent Scheduled Downtime* — The percent of time the equipment is not available to perform its intended function due to scheduled downtime events such as preventive maintenance. This time period does not include any maintenance delay downtime caused either by supplier or user. This calculation is intended to reflect the need for preventive maintenance based solely on equipment design.

$$equipment\ dependent\ scheduled\ downtime\ (\%) = \frac{equipment\ scheduled\ downtime \times 100}{(oper\text{-}time - (all\ maint\text{-}delay\ DT + out\text{-}of\text{-}spec\ input\ DT + fac\text{-}rel\ DT))}$$

6.4.5 *Supplier Dependent Scheduled Downtime* — The percent of time the equipment is not available to perform its intended function due to scheduled downtime events, such as preventive maintenance. This time period does not include any maintenance delay downtime caused by the user. This calculation is intended to reflect the need for preventive maintenance based solely on equipment design and supplier response to service.

$$supplier\ dependent\ scheduled\ downtime\ (\%) = \frac{equipment\ scheduled\ downtime \times 100}{(oper\text{-}time - (user\ maint\text{-}delay\ DT + out\text{-}of\text{-}spec\ input\ DT + fac\text{-}rel\ DT))}$$

6.5 *EQUIPMENT UTILIZATION* — The percent of time the equipment is performing its intended function during a specified time period.

6.5.1 *Operational Utilization* — The percent of productive time during operations time. This calculation is intended to be used for equipment utilization comparisons between operations with different work shift configurations, since it does not include non-scheduled time.

$$operational\ utilization\ (\%) = \frac{productive\ time \times 100}{operations\ time}$$

6.5.2 *Total Utilization* — The percent of productive time during total time. This calculation is intended to reflect bottom-line equipment utilization.

$$total\ utilization\ (\%) = \frac{productive\ time \times 100}{total\ time}$$

Table 1 RAM Measurement Metric Summary

EQUIPMENT RELIABILITY		
Metric	*How It Is Measured*	*Ref #*
$MTBF_p$: Mean (productive) time between failures	productive time/ # of failures that occur during productive time	6.2.1
E-$MTBF_p$: Mean (productive) time between equipment-related failures	productive time/ # of equipment-related failures that occur during productive time	6.2.2
MCBF: Mean cycles between failures	total equipment cycles/ # of failures	6.2.3
E-MCBF: Mean cycles between equipment-related failures	total equipment cycles/ # of equipment-related failures	6.2.4
EQUIPMENT AVAILABILITY		
Metric	*How It Is Measured*	*Ref #*
equipment dependent uptime (%)	equipment uptime × 100/(oper-time – (all maint-delay DT + out-of-spec input DT + fac-rel DT))	6.3.1
supplier dependent uptime (%)	equipment uptime × 100/(oper-time – (users maint-delay DT + out-of-spec input DT + fac-rel DT))	6.3.2
operational uptime (%)	equipment uptime × 100/ operations time	6.3.3
EQUIPMENT MAINTAINABILITY		
Metric	*How It Is Measured*	*Ref #*
MTTR: Mean time to repair	total repair time/ # of failures	6.4.1
E-MTTR: Mean time to repair for equipment-related failures	total repair time for equipment-related failures/ # of equipment-related failures	6.4.2
MTOL: Mean time off-line	total equipment downtime/ # of DT events	6.4.3
equipment dependent scheduled downtime (%)	equipment scheduled downtime × 100/(oper-time – (all maint-delay DT + out-of-spec input DT + fac-rel DT))	6.4.4
supplier dependent scheduled downtime (%)	equipment scheduled downtime × 100/(oper-time – (user maint-delay DT + out-of-spec input DT + fac-rel DT))	6.4.5
EQUIPMENT UTILIZATION		
Metric	*How It Is Measured*	*Ref #*
operational utilization (%)	productive time × 100/ operations time	6.5.1
total utilization (%)	productive time × 100/ total time	6.5.2

NOTE: oper-time = operational time, DT = Downtime, fac-rel = facilities related, maint-delay = maintenance delay

7 Uncertainty Measurement

7.1 The measures of equipment reliability, availability, and maintainability defined in Section 6 are single value estimates. They do not indicate the uncertainty or precision of the estimate. Precision varies depending upon the number of failures observed and the amount of productive time contained within the observation period.

7.2 Precision is described by calculating a lower and upper confidence limit for the $MTBF_p$ and presenting this interval along with the $MTBF_p$ point estimate.

7.3 These procedures assume that the failure rate is constant and the times between failures are independently distributed according to the exponential distribution. Therefore, there are no improvement or degradation trends and it is meaningful to calculate $MTBF_p$. Section 8 applies when the failure times indicate that a non-constant failure rate is present (for example, when there is reliability growth or degradation). Section 8 would typically apply during prototype reliability improvement testing.

7.4 Since MTTR distributions are unlikely to follow an exponential distribution assumption, applying these procedures to put confidence limits on MTTR would be inappropriate.

7.5 Note that all procedures and tables referred to in this section apply equally well to measuring the precision of estimates for similar metrics, where hours are replaced by cycles or units, for example. These procedures apply to E-$MTBF_p$ or E-MCBF in the same way. It is also appropriate to combine data from identical tools being used the same way, in order to improve the precision of $MTBF_p$ estimates.

7.6 *Calculation of Lower and Upper Confidence Limits* — To obtain lower and upper $MTBF_p$ limits, multiply the $MTBF_p$ estimate by factors obtained by table look-up (Tables A1-1 and A1-2 in Appendix 1). For the case when there are zero failures during the measurement period, lower confidence limit factors for the $MTBF_p$ are given in the first row of Table A1-1 (they multiply the amount of productive time that had no failures to obtain the desired $MTBF_p$ lower limit). There is no upper limit estimate for performance when there are zero failures.

7.6.1 *Calculation of the $MTBF_p$ Lower Limit* — Use Table A1-1 in Appendix 1 to obtain a $k_{r;conf}$ factor, where r is the number of failures observed during the measurement period and *conf* is the confidence level desired. The rows of Table A1-1 correspond to different values of r and the columns correspond to different values of *conf*. Confidence levels ranging from 80 percent to 95 percent are typical choices.

7.6.1.1 Since the equipment being measured has demonstrated (at a given confidence level) that it is at least as good as the $MTBF_p$ lower limit, this lower limit is an important and useful performance statistic, and is often used contractually.

7.6.1.2 Note that the factors in Table A1-1 for 90% confidence are less than 0.5 until the number of failures equals or exceeds 4. This means that when the number of failures is under 4, the $MTBF_P$ lower limit will be less than half the $MTBF_p$ estimate, and confidence intervals will be wide. From the point of view of precision, it is advantageous to have had 4 or more failures.

7.6.1.3 *Example*: During a given calendar quarter, a tool was productive for 1200 hours and had 6 failures. The $MTBF_p$ estimate is 1200/6 = 200 hours. A 90 percent lower limit factor from Table A1-1 (corresponding to $r = 6$ failures) is 0.570. That means that 200 × 0.570 = 114.0 hours is a 90 percent lower confidence limit for the true tool $MTBF_p$.

7.6.2 *Calculation of the $MTBF_p$ Upper Limit* — Use Table A1-2 in Appendix 1 to obtain a $k_{r;conf}$ factor, where r is the number of failures observed during the measurement period and *conf* is the confidence level desired. The rows of Table A1-2 correspond to different values of r and the columns correspond to different values of *conf*. Confidence levels ranging from 80 percent to 95 percent are typical choices.

7.6.2.1 *Example*: During a given calendar quarter, a tool was productive for 1200 hours and had 6 failures. The $MTBF_p$ estimate is 1200/6 = 200 hours. A 90 percent upper limit factor from Table A1-2 (corresponding to $r = 6$ failures) is 1.904. That means that 200 × 1.904 = 380.8 hours is a 90 percent upper confidence limit for the true tool $MTBF_p$.

7.6.3 *Calculation of a Confidence Interval for the $MTBF_p$* — Lower and upper $100 \times (1 - \alpha/2)$ confidence limits for the $MTBF_p$ can be combined to give a $100 \times (1 - \alpha)$ confidence interval. Here $\alpha/2$ is the chance of missing on either end of the interval. A 90 percent lower limit has an $\alpha/2 = 0.1$ chance of not being low enough to capture the true $MTBF_p$, and the same is true for a 90 percent upper limit. Therefore, a 90 percent lower limit and a 90 percent upper limit combine to give an 80 percent confidence interval. Similarly, a 95 percent lower limit and a 95 percent upper limit would combine to give a 90 percent confidence interval.

7.6.3.1 *Example*: During a calendar quarter, a tool was productive for 1200 hours and had 6 failures. The $MTBF_p$ estimate is 1200/6 = 200 hours. The 90 percent lower and upper limits are 114 and 380.8 respectively (see Sections 7.6.1 and 7.6.2). The interval (114, 380.8) is then an 80 percent confidence interval for the true tool $MTBF_p$.

7.6.4 *Calculation of the $MTBF_p$ Lower Bound when there are Zero Failures* — Use the first row of Table A1-1 (corresponding to $r = 0$) to obtain a $k_{0;conf}$ factor corresponding to the desired confidence level. Multiply the length of the measurement period by this factor to obtain the lower limit estimate.

7.6.4.1 *Example*: During a calendar quarter, a tool was productive for 1200 hours and had zero failures. From Table A1-1, the 90% confidence level lower limit factor is 0.434. That means that 1200 × 0.434 = 520.8 hours, is a 90% lower confidence limit estimate for the true tool $MTBF_p$.

7.6.5 Choosing a test length in order to be able to demonstrate a required $MTBF_p$ at a given confidence, we first must pick a maximum number of failures, *r*, that can occur during the test period and still allow us to confirm a required $MTBF_p$ objective at a given confidence level. Next, the length of test time needed can be calculated using the factors in Table A1-4 in Appendix 1. The required $MTBF_p$ is multiplied by a factor based on *r* and the desired confidence level to obtain the total test time needed.

7.6.5.1 Note that minimum test times are obtained by allowing no failures. The cost, however, of using a minimum test length is to increase the possibility of an acceptable tool failing the test by chance. As mentioned in the discussion in Section 6.2.1, it is advantageous to design a test that allows up to 4 failures, whenever possible.

7.6.5.2 *Example*: We would like to confirm a tool $MTBF_p$ of 400 hours at an 80% confidence level. We want to be able to pass a qualification test with 4 or less failures. We look up the appropriate factor from Table A1-4 and find 6.72. That means the length of test time required is 400 × 6.72 = 2688 hours. We can do this on one tool or split the test time across several tools. When we have accumulated 2688 hours and if 4 or less failures have occurred, the $MTBF_p$ objective of 400 hours will have been confirmed at (at least) the 80% confidence level.

8 Reliability Growth or Degradation Measurement

8.1 The previous calculations are meaningful only when the $MTBF_p$ (or MCBF) and E-$MTBF_p$ (or E-MCBF) are constant over the measurement period. If reliability is improving (typical during design verification and debug and also early life run-in) or if reliability is degrading (typical near the end of life for the piece of equipment, or if certain sub-assemblies have been over-stressed and are wearing out) then an overall $MTBF_p$ calculation is inappropriate and misleading and other methods must be used. Exact time of failure recording is required in order to detect reliability improvement or reliability degradation trends, and to fit appropriate models.

8.2 *Exact Time of Failure Recording* — Clock times of failure must be converted to durations of cumulative productive time as measured from the initial productive use of the tool (set as time 0). This is easily accomplished if total time is continuously monitored by duration within each of the six equipment states.

8.2.1 *Example*: A machine is intended for use during first shift operation five days a week. For simplicity, assume 100% productive utilization. After the first three weeks of use, it fails half-way through the day, and is not repaired until the start of the next day's operation. No more failures occur before the end of the first four weeks of operation. The exact time of failure is 124 hours (three weeks of 5 × 8 = 40 hours per week plus half of an 8 hour day). If a second failure occurred two hours into the third day of the fifth week, the exact time of failure would be 174 hours.

8.3 *Reliability Growth (Degradation) Models* — A useful family of reliability growth (degradation) models was developed by the U.S. Army Materials Systems Analysis Activity. These AMSAA models are described in Appendix 2, along with a general test for reliability growth (degradation) trends. Exact time of failure data is needed to test for trends, fit an AMSAA model, and test the fit for adequacy. The failures used to fit the model must occur during productive time (other failures can occur, but these are not used to fit reliability models).

APPENDIX 1
CONFIDENCE BOUND FACTORS

NOTICE: This appendix was approved as an official part of SEMI E10 by full letter ballot procedure. It offers detailed information related to Section 7.

A1-1 Introduction

A1-1.1 E-$MTBF_p$ may be substituted for $MTBF_p$ in all calculations in this section.

A1-1.2 Tables A1-1 and A1-2 contain factors that multiply an $MTBF_p$ point estimate to obtain upper and lower confidence limits. Table A1-1 applies in the common case where the equipment is observed for a fixed period of time and the number of failures that will occur is unknown in advance (time censored data). The alternative is failure censored data, where the number of failures is specified in advance and the equipment is observed until that many failures occur. Table A1-3 contains lower limit factors for failure censored data. Since failure censored data rarely occurs in tool or equipment reliability measurement, Table A1-3 is only included for completeness. The upper limit factors given in Table A1-2 apply to both kinds of censored data.

A1-1.3 Table A1-4 can be used to plan equipment assessment or qualification tests in order to be able to demonstrate a desired $MTBF_p$ at a given confidence level. In order to use Table A1-4, you must first choose a maximum number of failures, *r*, you might observe during the test period and still be able to meet the required $MTBF_p$ objective.

A1-1.4 For reference, here are the formulas for the lower and upper confidence limit factors for time censored data found in Tables A1-1 and A1-2:

$$MTBF_{LOWER} = \frac{2r}{X^2_{2r+2;1-\alpha}} \times MTBF_p$$

$$\textit{where } r = \# \textit{ of failures}$$

$$MTBF_{UPPER} = \frac{2r}{X^2_{2r;\alpha}} \times MTBF_p$$

A1-1.5 In both cases, the confidence level is 100 × (1 – α) that the true $MTBF_p$ is above $MTBF_{LOWER}$ and below $MTBF_{UPPER}$ and chi square distribution tables are used.

A1-1.6 For 0 fails, use:

$$MTBF_{LOWER} = \frac{\textit{productive time}}{-\log_e \alpha}$$

A1-1.7 Factors to use when there are 0 failures based on this formula are given in the first row of Table A1-1.

A1-1.8 For failure censored data, $MTBF_{UPPER}$ is the same, but the lower limit factor in Table A1-3 is:

$$MTBF_{LOWER} = \frac{2r}{X^2_{2r;1-\alpha}} \times MTBF_p$$

Table A1-1 1-Sided Lower Confidence Bound Factors for the $MTBF_p$ (Time or Cycle Censored Data or Fixed Length Test)

Use for time or cycle censored data to multiply the $MTBF_p$ or MCBF estimate to obtain a lower bound at the given confidence level.
For 0 failures, multiply the operating hours or cycles by the factor corresponding to the desired confidence level.

	CONFIDENCE LEVEL						
# FAILS *r*	60%	70%	80%	85%	90%	95%	97.5%
0	1.091	0.831	0.621	0.527	0.434	0.334	0.271
1	0.494	0.410	0.334	0.297	0.257	0.211	0.179
2	0.644	0.553	0.467	0.423	0.376	0.318	0.277
3	0.718	0.630	0.544	0.499	0.449	0.387	0.342
4	0.763	0.679	0.595	0.550	0.500	0.437	0.391
5	0.795	0.714	0.632	0.589	0.539	0.476	0.429
6	0.817	0.740	0.661	0.618	0.570	0.507	0.459
7	0.834	0.760	0.684	0.642	0.595	0.532	0.485
8	0.848	0.777	0.703	0.662	0.616	0.554	0.508
9	0.859	0.790	0.719	0.679	0.634	0.573	0.527
10	0.868	0.802	0.733	0.694	0.649	0.590	0.544
12	0.883	0.821	0.755	0.718	0.675	0.617	0.572
15	0.899	0.841	0.780	0.745	0.704	0.649	0.606
20	0.916	0.864	0.809	0.777	0.739	0.688	0.647
30	0.935	0.892	0.844	0.816	0.783	0.737	0.700
50	0.953	0.918	0.879	0.856	0.829	0.790	0.759
100	0.969	0.943	0.915	0.897	0.877	0.847	0.822
500	0.987	0.976	0.962	0.954	0.944	0.929	0.916

Table A1-2 1-Sided Upper Confidence Bound Factors for the $MTBF_p$

Use to multiply the $MTBF_p$ estimate to obtain an upper bound at the given confidence level (time censored or failure censored data).

	CONFIDENCE LEVEL						
# FAILS *r*	60%	70%	80%	85%	90%	95%	97.5%
1	1.958	2.804	4.481	6.153	9.491	19.496	39.498
2	1.453	1.823	2.426	2.927	3.761	5.628	8.257
3	1.313	1.568	1.954	2.255	2.722	3.669	4.849
4	1.246	1.447	1.742	1.962	2.293	2.928	3.670
5	1.205	1.376	1.618	1.795	2.055	2.538	3.080
6	1.179	1.328	1.537	1.687	1.904	2.296	2.725
7	1.159	1.294	1.479	1.610	1.797	2.131	2.487
8	1.144	1.267	1.435	1.552	1.718	2.010	2.316
9	1.133	1.247	1.400	1.507	1.657	1.917	2.187
10	1.123	1.230	1.372	1.470	1.607	1.843	2.085
12	1.108	1.203	1.329	1.414	1.533	1.733	1.935
15	1.093	1.176	1.284	1.357	1.456	1.622	1.787
20	1.077	1.147	1.237	1.296	1.377	1.509	1.637
30	1.060	1.115	1.185	1.231	1.291	1.389	1.482
50	1.044	1.085	1.137	1.170	1.214	1.283	1.347
100	1.029	1.058	1.093	1.115	1.144	1.189	1.229
500	1.012	1.025	1.039	1.049	1.060	1.078	1.094

Table A1-3 1-Sided Lower Confidence Bound Factors for the $MTBF_p$ (Failure Censored Data)

Use for failure censored data to multiply the $MTBF_p$ estimate to obtain a lower bound at the given confidence level. Failure censored data means the test or observation period lasts as long as needed to obtain a preset number of failures.

	CONFIDENCE LEVEL						
# FAILS *r*	60%	70%	80%	85%	90%	95%	97.5%
1	1.091	0.831	0.621	0.527	0.434	0.334	0.271
2	0.989	0.820	0.668	0.593	0.514	0.422	0.359
3	0.966	0.830	0.701	0.635	0.564	0.477	0.415
4	0.958	0.840	0.725	0.665	0.599	0.516	0.456
5	0.955	0.849	0.744	0.688	0.626	0.546	0.488
6	0.954	0.856	0.759	0.706	0.647	0.571	0.514
7	0.953	0.863	0.771	0.721	0.665	0.591	0.536
8	0.954	0.869	0.782	0.734	0.680	0.608	0.555
9	0.954	0.874	0.791	0.745	0.693	0.623	0.571
10	0.955	0.878	0.799	0.755	0.704	0.637	0.585
12	0.956	0.886	0.812	0.771	0.723	0.659	0.610
15	0.958	0.895	0.828	0.790	0.745	0.685	0.639
20	0.961	0.906	0.846	0.812	0.772	0.717	0.674
30	0.966	0.920	0.870	0.841	0.806	0.759	0.720
50	0.971	0.935	0.896	0.872	0.844	0.804	0.772
100	0.978	0.952	0.923	0.906	0.885	0.855	0.830
500	0.989	0.978	0.964	0.956	0.945	0.930	0.918

Table A1-4 Test Length Guide

Use to determine the test time needed to demonstrate a desired $MTBF_p$ at a given confidence level if *r* failures occur. Multiply the desired $MTBF_p$ by the *k* factor corresponding to *r* and the confidence level.

	k FACTOR FOR GIVEN CONFIDENCE LEVELS					
# FAILS *r*	50%	60%	75%	80%	90%	95%
0	0.693	0.916	1.39	1.61	2.30	3.00
1	1.68	2.02	2.69	2.99	3.89	4.74
2	2.67	3.11	3.92	4.28	5.32	6.30
3	3.67	4.18	5.11	5.52	6.68	7.75
4	4.67	5.24	6.27	6.72	7.99	9.15
5	5.67	6.29	7.42	7.90	9.28	10.51
6	6.67	7.35	8.56	9.07	10.53	11.84
7	7.67	8.38	9.68	10.23	11.77	13.15
8	8.67	9.43	10.80	11.38	13.00	14.43
9	9.67	10.48	11.91	12.52	14.21	15.70
10	10.67	11.52	13.02	13.65	15.40	16.96
15	15.67	16.69	18.48	19.23	21.29	23.10
20	20.68	21.84	23.88	24.73	29.06	30.89

APPENDIX 2
RELIABILITY GROWTH OR DEGRADATION MODELS

NOTICE: This appendix was approved as an official part of SEMI E10 by full letter ballot procedure. It offers detailed information related to Section 8.

A2-1 Introduction

A2-1.1 E-MTBF$_p$ may be substituted for MTBF$_p$ in all calculations in this section.

A2-1.2 If the times between failures (known as "interarrival times") of a repairable system or piece of equipment are independent random times sampled from the same exponential distribution, then the (theoretical) *rate of occurrence of failures* ("ROCOF") is a constant λ and the MTBF$_p$ is just $1/\lambda$. This situation is known in the reliability literature as a *homogeneous poisson process* (HPP). An HPP assumption underlies the definition of MTBF$_p$ given in Section 6, and the confidence limit factors described in Section 7 and Appendix 1. These concepts are described in detail in Ascher and Feingold [1] and Tobias and Trindade [2].

A2-1.3 If reliability is either improving or degrading with time, then the ROCOF is no longer a constant and a MTBF$_p$ calculation will be misleading.

A2-1.4 This appendix contains a simple test for trend that may be applied if a time-varying ROCOF is suspected, as well as a description of a well known and powerful model that may be used when reliability improvement trends are evident in the equipment failure time data.

A2-2 Testing for Trends

A2-2.1 A non-parametric *reverse arrangement test* (RAT) devised by Kendall [3] and further developed into a table by Mann [4] will be described. Begin by writing the interarrival times in the order they occurred. For a period with r failures, these might be $X_1, X_2, \ldots, X_r$. Starting from left to right, define a reversal as any instance in which a lesser value occurs before any subsequent greater value in the sequence. In other words, any time we have $X_i < X_j$ and $i < j$, we count it as a reversal. For example, suppose a piece of equipment has $r = 4$ failures at 30, 160, 220, and 360 hours of productive time. The interarrival times are 30, 130, 60, and 140. The total number of reversals is 3 + 1 + 1 = 5.

A2-2.2 A larger than expected number of reversals indicates an improving trend; a smaller number of reversals than expected indicates a degradation trend.

A2-2.3 For r up to 12, use Table A2-1 below (adapted from [2]) to determine whether a given number of reversals, R, is statistically significant at the $100 \times (1 - \alpha)$ confidence level.

A2-2.4 For r greater than 12, approximate critical values for the number of reversals (based on Kendall's normal approximation) can be calculated from:

$$R_{(r;\,1\text{-}\alpha)} = z_{critical}\sqrt{\frac{(2r+5)(r-1)r}{72}} + \frac{r(r-1)}{4} - \frac{1}{2}$$

Table A2-1 Critical Values $R_{r;1-\alpha}$ the Number of Reversals for the Reverse Arrangement Test at a Given Confidence Level

Sample Size	*Single-Sided Lower Critical Value (Too Few Reversals Provide Evidence of Degradation)*			*Single-Sided Upper Critical Value (Too Many Reversals Provide Evidence of Improvement)*		
r	99%	95%	90%	90%	95%	99%
4		0	0	6	6	
5	0	1	1	9	9	10
6	1	2	3	12	13	14
7	2	4	5	16	17	19
8	4	6	8	20	22	24
9	6	9	11	25	27	30
10	9	12	14	31	33	36
11	12	16	18	37	39	43
12	16	20	23	43	46	50

A2-2.5 In this equation $z_{critical}$ comes from the critical values of the standard normal distribution (for 90% significance, $z_{critical}$ = 1.282, for 95% significance, $z_{critical}$ = 1.645, and for 99% significance, $z_{critical}$ = 2.33). The formula calculates the critical value for detecting an improvement trend. For degradation trends (a small number of reversals) use $(r)(r - 1)/2$ minus $R_{r;1-\alpha}$ as the critical value. Note that $(r)(r - 1)/2$ just the total possible number of reversals when there are r failures.

A2-2.6 For example, with 17 failures, the formula for $R_{r;1-\alpha}$, using 95% significance, gives a critical number of reversals of $R_{17,95}$ = 88. The maximum number of reversals is 17 × 16/2 = 136. That means that observing 88 or more reversals signals a likely improvement trend, while observing 136 − 88 = 48 or less reversals signals a likely degradation trend.

A2-2.7 The example given in the next section shows an application for the reverse arrangement test using Table A2-1.

A2-2.8 The *AMSAA Reliability Growth Model*: Assume the sequence of interarrival time indicates an improvement trend. This will typically be the case during reliability improvement testing, where failures are analyzed down to root causes and actions are taken to improve the equipment's reliability. Duane [5] observed that a plot of t_k/k versus t_k, where t_k is the system age at the time of kth failure, typically appears linear on log versus log graph paper. The slope β of this line measures the rate of reliability growth. Typical empirical values of β lie between 0.3 and 0.6. Crow [6] developed this empirical observation into the power relationship model used by the U.S. Army Materials Systems Analysis Activity (AMSAA model). This model has proved successful in a wide range of applications.

A2-2.9 The AMSAA model assumes that during reliability improvement testing the $MTBF_p$ is improving with time and has an instantaneous value denoted by $MTBF_I$ (t). When the test ends at time T, the $MTBF_p$ becomes a constant with the value $MTBF_I$ (T). An estimate of the $MTBF_p$ after a test of T hours with r failures is given by:

$$MTBF_I(T) = \frac{T}{r \times (1 - \beta)} \quad (1)$$

A2-2.10 In this equation, β is the reliability improvement (Duane) slope, β is estimated by

$$\beta = 1 - \frac{r - 1}{\sum_{i=1}^{r} \ln \frac{T}{t_i}} \quad (2)$$

using the *modified maximum likelihood estimates* given by Crow [6]. Crow developed confidence limits for $MTBF_I$ (T) that are described in [2] and [6].

A2-2.11 *Example*: During a calendar quarter a tool has 550 hours of productive time. Eleven failures were recorded at the following points of productive time: 18, 20, 35, 41, 67, 180, 252, 287, 390, 410, and 511 hours. Determine whether there appears to be an improvement trend and use the AMSAA model to estimate the achieved $MTBF_I$ at the end of the quarter.

A2-2.12 *Solution:* The interarrival times are: 18, 2, 15, 6, 26, 113, 72, 35, 103, 20, and 101. The number of reversals is 7 + 9 + 7 + 7 + 5 + 0 + 2 + 2 + 0 + 1 = 40. Using Table A2-1, this is significant at greater than the 95% confidence level, indicating an improvement trend is likely. Figure A2-1 shows the Duane plot, which appears to show a linear improvement trend on log-log paper. The AMSAA model equations give an improvement slope estimate of 0.43 and an instantaneous $MTBF_P$ estimate at 550 hours of 87.2. Note that a standard calculation ignoring the improvement trend would yield an $MTBF_P$ estimate of 550/11 = 50, which is a 43% underestimate.

A2-2.13 Figure A2-2 summarizes the recommended procedure to follow when analyzing system or equipment reliability data, with appropriate references to SEMI E10 sections or appendices.

A2-3 References

1. Ascher, H. and H. Feingold, *Repairable Systems Reliability*, Marcel Dekkar, Inc., New York, 1984
2. Tobias, P.A. and D.C. Trindade, *Applied Reliability, Second Edition*, Van Nostrand Reinhold, Inc., New York, 1995
3. Kendall, M.G., "A New Measure of Rank Correlation", *Biometrika*, 1938, volume 30, pages 81-93
4. Mann, H.B., "Nonparametric Test Against Trend" *Econometrica*, 1945, volume 13, pages 245-25
5. Duane, J.T., "Learning Curve Approach to Reliability Monitoring," *IEEE Transactions on Aerospace*, 1964, volume 2, pages 563-566
6. Crow, L.H., "Reliability Analysis for Complex Repairable Systems," *Reliability and Biometry*, F. Proschan and R.J., Serfling, eds., SIAM, Philadelphia, 1974; pp. 126-134

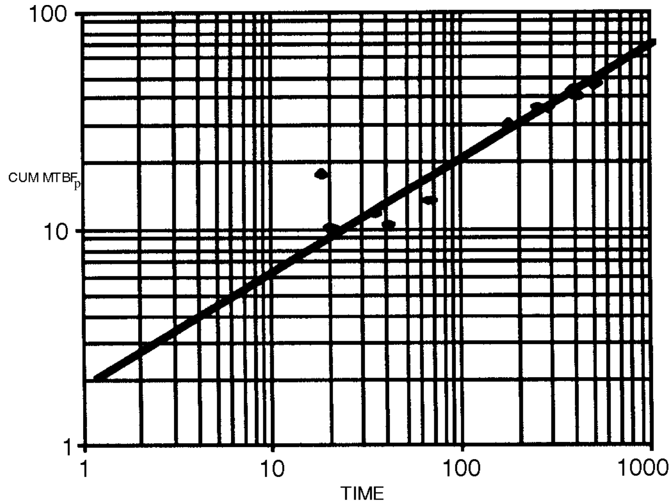


Figure A2-1
Duane Plot of CUM MTBF$_p$ vs. Time

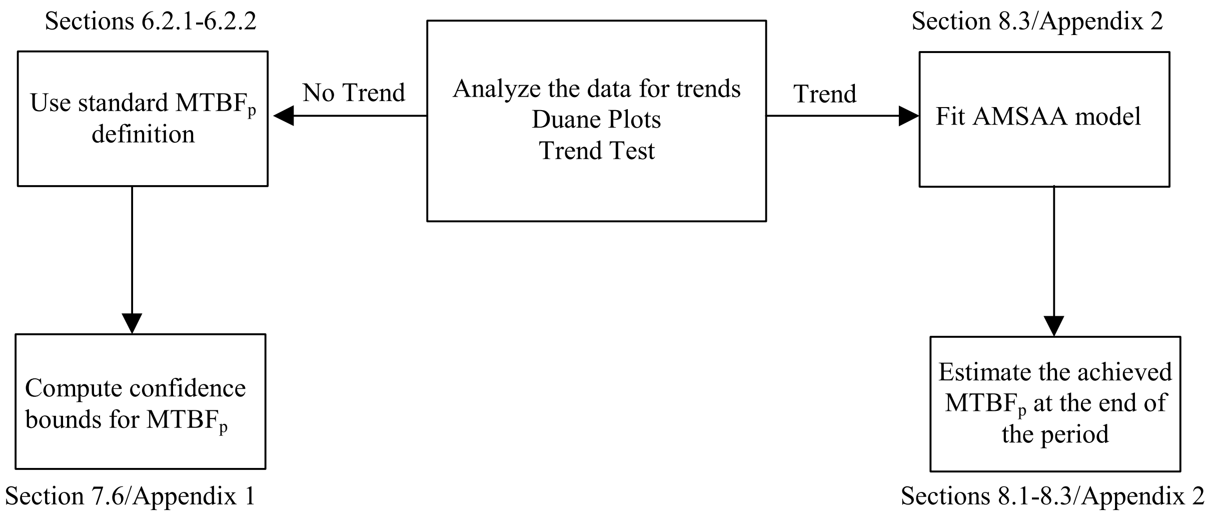


Figure A2-2
Flow Chart for Reliability Data Analysis

RELATED INFORMATION 1
MULTI-PATH CLUSTER TOOL RAM METRICS

NOTICE: This related information is not an official part of SEMI E10 and was derived from work done by the SEMI NA Cluster Tool RAM Metrics Task Force. This related information was approved for publication by full letter ballot on October 15, 2003.

R1-1 Introduction

R1-1.1 This related information presents tracking requirements and standard metrics for evaluating multi-path cluster tool reliability, availability, and maintainability (RAM) performance. The metrics in the main body of SEMI E10 apply to non-cluster or single-path cluster tools and individual modules in a straightforward manner. While these entities are either entirely "up" (i.e., in one of the SEMI E10 uptime states) or entirely "down" (i.e., in one of the SEMI E10 downtime states), multi-path cluster tools may still be capable of processing with some modules in an unscheduled downtime state. Furthermore, the effect of module unscheduled downtime on multi-path cluster tool performance depends on the specific multi-path cluster tool configuration and the combination of modules in an unscheduled downtime state at each point in time.

R1-1.2 Because module performance provides a sufficient lowest common denominator for evaluating multi-path cluster tool performance, all metrics in this related information are calculated as functions of module-level data only. Specific module tracking requirements are presented. The metrics, Total Failure Rate (TFR) and Cluster-Tool Mean Time to Repair ($MTTR_{CT}$), provide simple evaluations of aggregate module reliability and maintainability.

R1-1.3 Other metrics are based on the specific combinations of modules and process paths, defined here as process flows.

R1-1.3.1 A *process path* is a specific set of modules for which each module is unique and has no alternative modules.

R1-1.3.2 A *process flow* is a defined set of modules that is used to achieve a process, where any multi-path cluster tool may have one or more such process flows. A process flow may include alternative modules at one or more steps of the process. A process flow may therefore contain one or many process paths.

R1-1.4 A method of temporal mapping, defined in this related information, is used to generate a history of process flow and multi-path cluster tool states from individual module states. Multi-path cluster tool availability is then evaluated as the aggregate process flow availability. Multi-path cluster tool reliability is evaluated as the expected, or mean, productive time between all process flows being in unscheduled downtime.

R1-2 Module Tracking Requirements

R1-2.1 Multi-path cluster tool metrics require the tracking of SEMI E10 state data from all of the modules that impact the RAM or productivity of a multi-path cluster tool or its process flows. This set of modules includes processing and non-processing modules.

R1-2.1.1 *processing module* — an indivisible production entity within an equipment system, e.g., a processing chamber or station within a cluster tool. (SEMI E79)

R1-2.1.2 *non-processing module* — an equipment entity that supports the movement or conditioning of units through the system, such as, robotic handler, load/unload lock, pre-aligner.

R1-2.2 Multi-path cluster tool metrics require tracking at the module level of at least productive states, unscheduled downtime states, scheduled downtime states, and other *neutral* states that are not in the first three categories. Tracking of these states at the level of the multi-path cluster tool as a whole is insufficient for accurate evaluation of performance. Specific requirements for tracking these states at the module level, as well as requirements for handling the other SEMI E10 states, are presented here.

R1-2.2.1 Productive state shall be tracked for each module. For process modules, the productive time shall include time for active loading and unloading of the process module. Waiting times or inactive times, including waiting for load, waiting for unload, and process suspend times shall be specifically excluded from productive time. Times for heating, cooling, purging, cleaning, etc., that are specified as part of process recipes shall be tracked as productive time. However, similar times that are not specified as part of process recipes shall be specifically excluded from productive time.

NOTE 1: Productive state events may be derived from SEMI E58 (ARAMS) state change data or the SEMI E116 (EPT) module BUSY state events where the module or whole multi-path cluster tool is known to be in a "manufacturing" state and the SEMI E116 task type is either "Process" or "Support."

R1-2.2.2 Unscheduled downtime state shall be tracked for each module. Tracking of unscheduled downtime state for the multi-path cluster tool as a whole is not sufficient. A module cannot be in productive and unscheduled downtime states at the same time. Each contiguous instance of unscheduled downtime state for a module is a module failure. Subsequent substate events within the same instance of unscheduled downtime state shall not to be counted as additional failures.

R1-2.2.3 Scheduled downtime state shall be tracked for each module. Tracking of scheduled downtime state for the multi-path cluster tool as a whole is not sufficient. A module cannot be in productive and scheduled downtime states at the same time. Instances of scheduled downtime shall not to be counted as failures.

R1-2.2.4 Time in standby and engineering states shall not be considered as either productive time, scheduled downtime, or unscheduled downtime at the module level. For the purpose of tracking multi-path cluster tool states and calculating multi-path cluster tool and process flow metrics, modules in these states are considered as being in a *neutral* state.

R1-2.2.5 Non-scheduled time that is tracked for the multi-path cluster tool as a whole is omitted from operations time in calculating multi-path cluster tool and process flow RAM metrics, as it is with the other SEMI E10 metrics from the main body of the specification. Non-scheduled time that is allocated to some modules but not other modules, if any, shall be handled differently, as follows.

R1-2.2.5.1 For new modules under installation that have not yet been used for their intended function, those modules shall be considered as non-existent in the cluster-tool configuration.

R1-2.2.5.2 For installed modules that have been used, non-scheduled time state shall be treated as a *neutral* state.

R1-2.3 To calculate these metrics, an observation period shall be defined and agreed upon by the user and/or the supplier. Section A1-1.3 provides some guidance on establishing the observation period time needed to demonstrate a desired $MTBF_p$ at a given confidence level.

R1-2.3.1 *observation period time* — elapsed calendar time (e.g., weeks, months, quarters) observing and tracking tool performance. No allowance is made for the number of modules in a cluster tool.

R1-3 Total Failure Rate and Cluster-Tool Mean Time to Repair

R1-3.1 *Total Failure Rate (TFR)* — total count of module-level failure onsets, tracked according to the requirements in Section R1-2, divided by the observation period time. This metric characterizes the frequency of repairs where failures on separate modules are presumed to require independent repair actions. TFR is an indicator of reliability and maintainability. TFR is defined as:

$$TFR = \frac{\sum_{all\ modules} count\ of\ module\ failure\ onset\ events}{observation\ period\ time}$$

NOTE 2: For different multi-path cluster tools with comparable module failure rates, a multi-path cluster tool with fewer modules is expected to have better performance according to this metric than one with more modules. However, the multi-path cluster tool with more modules may have a better aggregate intended process flow uptime ($Uptime_{CT\text{-}IPF}$), as defined in Section R1-7.3.

R1-3.2 *Cluster-Tool Mean Time to Repair ($MTTR_{CT}$)* — mean time to correct a module-level failure and return the module to a condition where it can perform its intended function; the sum of all repair time on all modules (elapsed module time, not necessarily total work-hours) incurred during a specified observation period time (including equipment and process test time, but not including maintenance delay downtime), divided by the total number of failure onset events during that period.

$$MTTR_{CT} = \frac{\sum_{all\ modules} repair\ time}{\sum_{all\ modules} count\ of\ module\ failure\ onset\ events}$$

NOTE 3: This is the same equation as MTTR for non-cluster and single-path cluster tools. However, because a multi-path cluster-tool may have repairs occurring simultaneously, the sum of repair time is not constrained to the duration of the observation period.

R1-3.3 For any module, a failure onset event is the first chronological event of a contiguous instance of unscheduled downtime. To ensure that over multiple observation periods, neither failure onset events nor repair time is ever double-counted, the following rules shall be followed.

R1-3.3.1 Failure onset events that occur during the observation period are counted in TFR and $MTTR_{CT}$ regardless of when those failures are resolved.

R1-3.3.2 Failure onset events that occur before the observation period are not counted in TFR and $MTTR_{CT}$, even if those failures are not resolved until during or after the observation period.

R1-3.3.3 For a failure whose onset occurs outside of the observation period, the portion of its repair time that occurs within the observation period is still counted in $MTTR_{CT}$.

NOTE 4: These metrics also may be calculated for any multi-module tool even if that tool is not a multi-path cluster tool. For a system failure that arises from multiple module failures, the additional severity of this case and the independence of module repair efforts are reflected in this metric. For standard evaluation of a non-multi-path cluster tool, however, the tool is considered to be either entirely in the unscheduled downtime state or not in the unscheduled downtime state.

R1-3.4 These metrics are not compatible with approaches based on renewal cycle models where uptime and downtime are assumed to be mutually exclusive. As such, subsequent module failures may occur even while failures are already in progress on other modules. Other renewal cycle results (e.g., the limiting probability of finding the system "up" (or "down") when approaching the system at random) similarly may not apply.

R1-4 Temporal Mapping

R1-4.1 Temporal mapping provides an output state history as a function of constituent input state histories. For each event when at least one of the modules changes state, the states of the process flows and/or cluster tool may change. For the metrics in this related information, cluster-tool and process-flow state histories are generated as functions of module state histories on an event-by-event basis in temporal, or chronological, order. The metrics themselves are calculated as functions of these output state histories. For reference, this technique may be regarded as generating a type of convolution of constituent state models.

R1-4.2 Figure R1-1 presents an example of temporal mapping. The constituent input states for two modules, M1 and M2, are shown over the observation period t = 0 to t = 10. An output state is mapped temporally as a function of the module states, where if either module is "down" or both modules are "down," the output state is "down." Note that transition events for the output state history are the union set of the transition events for the constituent input state histories.

R1-4.3 In a near-real-time tracking system, temporal mapping may be performed as each event is generated and received by the tracking system. Temporal mapping also may be performed afterwards as a batch process. Regardless, the logical process is the same. Depending on the mapping to be performed, a different logic function is applied at each input state transition event to derive an output state value as a function of the constituent input state values. Two specific temporal mapping functions are used in metrics in this related information:

R1-4.3.1 Process flow "up/scheduled downtime/ unscheduled downtime" states from module "up/scheduled downtime/unscheduled downtime" states as a function of supplier-defined and/or user-defined process flows.

R1-4.3.2 Multi-path cluster tool "productive/neutral/ unscheduled downtime" as a standard function, presented herein, of module "productive/not-productive" states and process-flow "up/scheduled downtime/unscheduled downtime" states.

NOTE 5: While it may be theoretically possible to model the desired output states using Harel notation and modeling concepts, output state complexity may be confounded by the combinatorial nature of multi-path cluster tools and their process flows. For this application, the temporal mapping approach is much more straightforward.

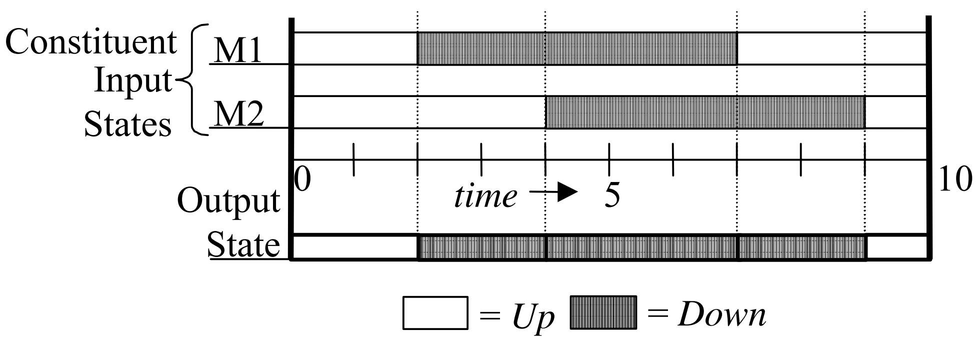


Figure R1-1
An Example Of Temporal Mapping

R1-5 Modeling Process Flows

R1-5.1 In order to evaluate multi-path cluster tool availability and reliability, the set of process flows shall be defined for the multi-path cluster tool. It is important to differentiate between all the process flows that are theoretically possible on a given multi-path cluster tool configuration and those intended process flows (IPF) that are actually intended for operational use (i.e., performing its intended function). For meaningful agreement between any two parties on the metrics presented in this related information, first there shall be documented agreement on the set of IPFs used for evaluation, so that any analyst with the module state histories can calculate the same values for the metrics. First, the general case of "up/down" states for an IPF is presented, and then later the distinction between unscheduled downtime and total (i.e., scheduled and unscheduled) downtime for an IPF is presented.

R1-5.2 An IPF "up/down" state is modeled as a network flow through the modules that make up that IPF. If there is "connectivity" through the IPF network, then the IPF is "up;" otherwise it is "down." The modules in an IPF network have series and parallel relationships that determine the connectivity through the network. Mathematically, each module and each IPF has a state value equal to 1 when the state is "up" and 0 when the state is "down." For example,

$$M_i = \left\{ \begin{array}{l} \textit{1, if module i is up} \\ \textit{0, if module i is down} \end{array} \right\}$$

R1-5.3 The general process steps within an IPF have a mutually serial relationship (i.e., if connectivity is not possible through any single step, then connectivity is not possible through the network). This is illustrated in Figure R1-2. The IPF state value for serial constituents is calculated as the product of the constituent state values (e.g., IPF = $\Pi_{\text{i=1 to 4}}$ Si = S1 × S2 × S3 × S4).

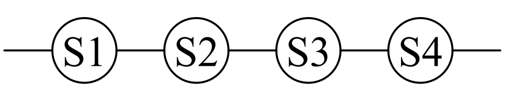


Figure R1-2
Serial Process Steps Within An IPF

R1-5.4 At any general process step, S_x, the set of alternative modules, Ai (if any are present), have a mutually parallel relationship (i.e., if any one of the alternative modules is up, then connectivity through that step is still possible). This is illustrated in Figure R1-3. The state value through this step is calculated as:

IPF = 1 - $\Pi_{\text{i=1 to 3}}$ (1 − Ai)

= 1 − [(1 − A1) × (1 − A2) × (1 − A3)]

If any alternative module is "up," the expression in the square brackets evaluates to zero, and the IPF state value evaluates to 1, or "up." If all of the alternative modules are "down," the expression in the square brackets evaluates to 1, and the IPF state value evaluates to 0, or "down."

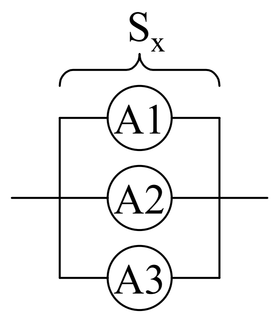


Figure R1-3
Parallel Alternative Modules At A Process Step

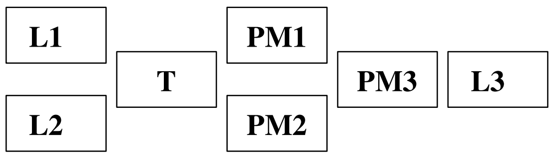
NOTE 6: In general network modeling, it is possible to have complicated multi-constituent structures in parallel with other multi-constituent structures. At the time of this writing, the need for such structures in evaluating multi-path cluster tool RAM is not anticipated. Therefore, this exposition is limited to serial relationships amongst the process steps and single-constituent parallel relationships for alternatives within any one step. To model multi-path cluster tool systems that exceed these limitations, the modeler is encouraged to consult any text on the modeling of coherent systems for reliability.

R1-5.5 For almost all systems, there will be a subset of modules that will appear in every IPF regardless of any process differentiation, called the *key group*. The key group includes support modules (e.g., transport, load locks), common process modules that are used by every IPF, and the platform itself. A key group may include alternative modules such as multiple load locks or multiple cooling stations. The key group's relationship to all IPFs is such that if the key group is down, all IPFs are down. Therefore, the key group has a serial relationship to each IPF. By modeling a key group and leveraging it in calculations, substantial redundant calculations are avoided. Furthermore, understanding which modules belong to the key group also helps in understanding and improving overall system reliability.

R1-5.6 Two examples are now presented to illustrate how to model IPFs, including modeling of the key group and of IPF state functions.

R1-5.6.1 *Example 1* — This example, shown in Figure R1-4, is of a multi-path cluster tool with seven modules. L1 and L2 are load lock modules that are used to load units into the tool. A single transport arm, T, performs all point-to-point transportation. The first process module visited by any unit is either PM1 or PM2, after which every unit visits PM3. Lastly, L3 is a load lock that is used to unload units from the multi-path cluster tool.

R1-5.6.1.1 The key group, K, as shown in Figure R1-5, is made up of the three load locks and the transport, which are the common support modules for this multi-path cluster tool used by any unit. Since all modules visit PM3 regardless of any IPF distinction, PM3 also is included in the key group in order to simplify calculation. Any other system-level failure issues may be allocated to the abstract platform module, P.



Li = Load Lock i, i = 1, 2, 3
PMj = Process Module j, j = 1, 2, 3
T = Transport Module

Figure R1-4
Multi-Path Cluster Tool Modules, Example 1

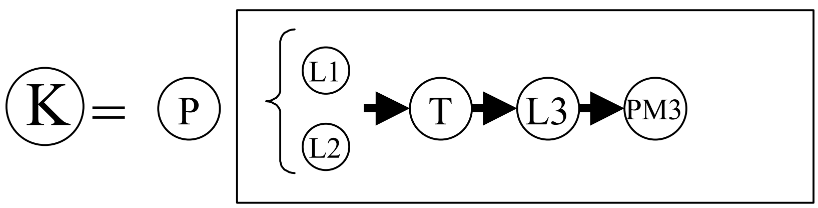


Figure R1-5
Key Group, Example 1

R1-5.6.1.2 The state value function for the key group is K = P × [1 − (1 − L1) × (1 − L2)] × T × L3 × PM3. For reference, the equivalent truth table for this logic is shown in Table R1-1:

Table R1-1 Truth Table for Key Group, Example 1

P	*L1*	*L2*	*T*	*L3*	*PM3*	*K*
1	1	1	1	1	1	1
1	1	0	1	1	1	1
1	0	1	1	1	1	1
else						0

R1-5.6.1.3 IPF1 is a general IPF that uses the key group and either process module PM1 or PM2, as shown in Figure R1-6.

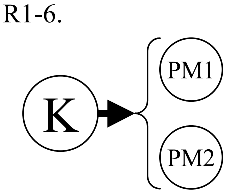


Figure R1-6
IPF1, Example 1

R1-5.6.1.4 The state value function for IPF1 = K × [1 − (1 − PM1) × (1 − PM2)]. The equivalent truth table is shown in Table R1-2:

Table R1-2 Truth Table for the State Function, Example 1

K	*PM1*	*PM2*	*IPF1*
1	1	1	1
1	1	0	1
1	0	1	1
else			0

R1-5.6.1.5 IPF2 represents a process engineering issue where PM2 is not sufficiently matched in performance to PM1. Therefore for certain processes, all units are restricted to go through PM1 only as shown in Figure R1-7.

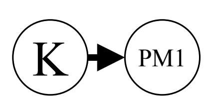


Figure R1-7
IPF2, Example 1

R1-5.6.1.6 The state value function for IPF1 = K × PM1. The equivalent truth table is trivial and is therefore not shown.

R1-5.6.2 *Example 2* — This example, as shown in Figure R1-8, is of a more complicated coat/develop system that has 56 total modules, including four load locks (L1-L4), four common transport robots (R1-R4), four coat stations, four develop stations, and four arrays of heat/chill plates with ten modules in each array.

R1-5.6.2.1 The key group, K, contains the platform, the four load locks, and the four transport robots, as shown in Figure R1-9. There are no process modules that are used in every IPF, therefore no process modules appear in K.

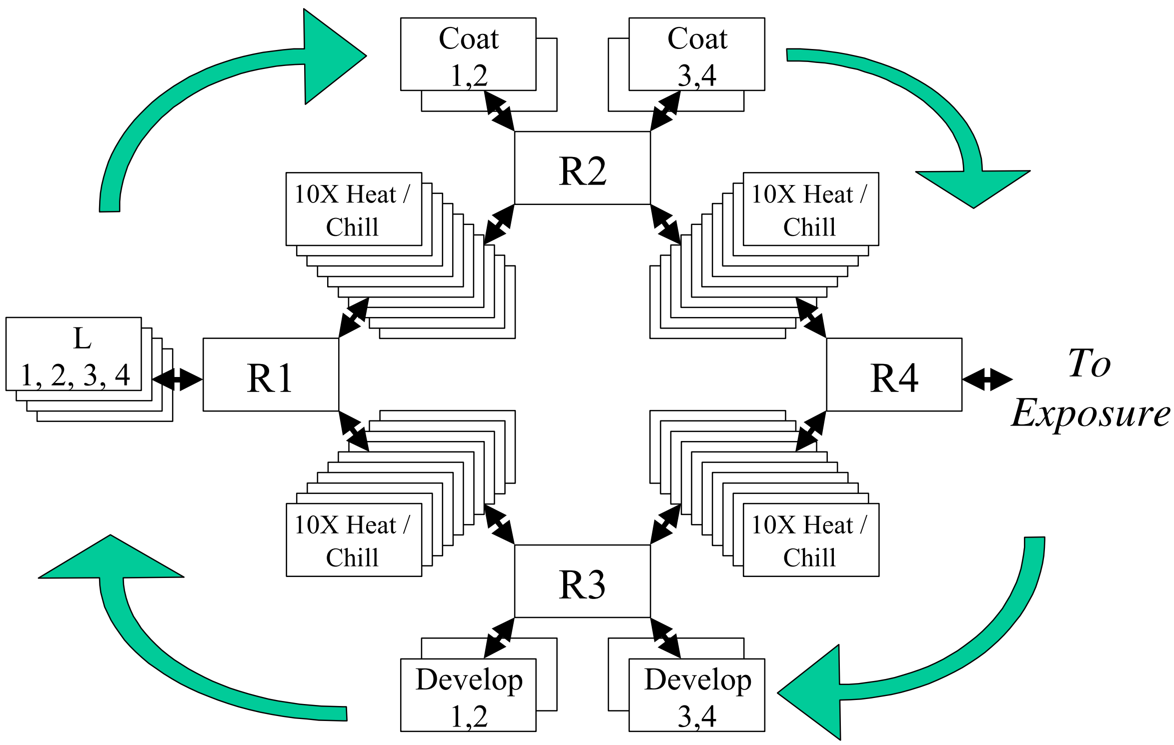


Figure R1-8
Modules For A Coat/Develop System

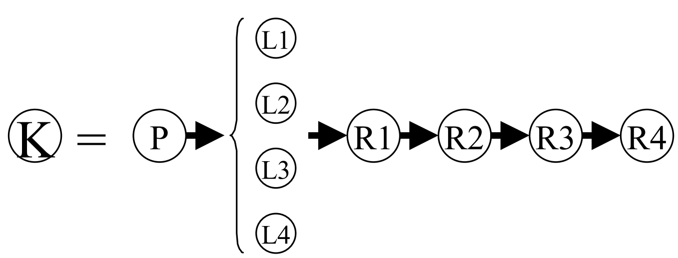


Figure R1-9
Key Group Modules, Example 2

R1-5.6.2.2 The state value function for the key group is $K = P \times [1 - \Pi_{i = 1 \text{ to } 4} (1 - Li)] \times \Pi_{j=1 \text{ to } 4} Rj$, which can be expanded to:

$$K = P \times [1 - (1 - L1) \times (1 - L2) \times (1 - L3) \times (1 - L4)] \times R1 \times R2 \times R3 \times R4$$

R1-5.6.2.3 The equivalent truth table is shown in Table R1-3:

Table R1-3 Truth Table for State Function, Example 2

P	*L1*	*L2*	*L3*	*L4*	*R1*	*R2*	*R3*	*R4*	*K*
0	any	any	any	any	any	any	any	any	0
1	0	0	0	0	any	any	any	any	0
any	any	any	any	any	0	any	any	any	0
any	any	any	any	any	any	0	any	any	0
any	any	any	any	any	any	any	0	any	0
any	any	any	any	any	any	any	any	0	0
else									1

NOTE 7: This truth table emphasizes the subsets that bring the key group "down," which are called *minimum cut sets*, rather than the subsets that keep the key group "up," called *minimum path sets*.

R1-5.6.2.4 IPF1 has 13 steps and each step has two alternative modules, as shown in Figure R1-10.

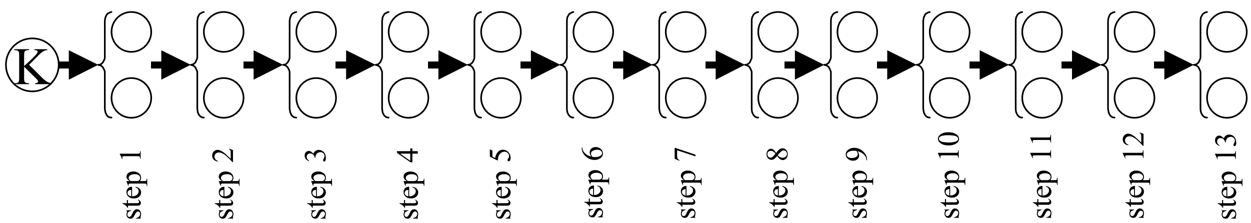


Figure R1-10
Module Configuration For IPF1, Example 2

R1-5.6.2.5 The state value function for $IPF1 = K \times \Pi_{i=1 \text{ to } 13}[1 - (1 - PM_{i,1}) \times (1 - PM_{i,2})]$. The equivalent truth table is highly redundant and is therefore omitted.

R1-5.6.2.6 IPF2 has the same 13 steps as IPF1. However due to process matching issues, all units are restricted to a single process module at steps 1, 5, 9, and 13, as shown in Figure R1-11.

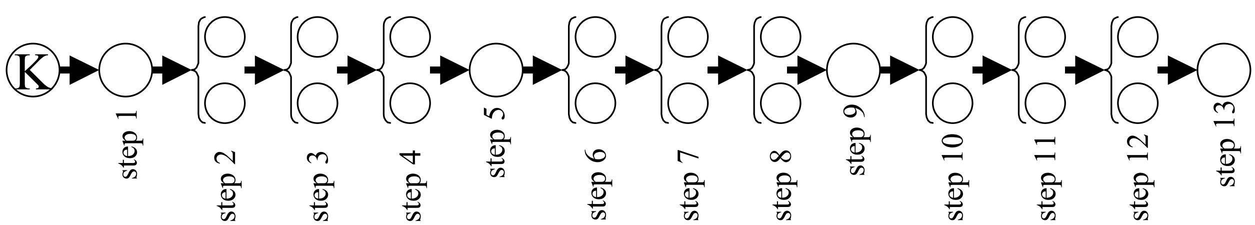


Figure R1-11
Module Configuration For IPF2, Example 2

R1-5.6.2.7 The state value function for $IPF2 = K \times PM_{1,1} \times PM_{5,1} \times PM_{9,1} \times PM_{13,1} \times \Pi_{i=\{2\text{-}4,\ 6\text{-}8,\ 10\text{-}12\}} [1 - (1 - PM_{i,1}) \times (1 - PM_{i,2})]$

R1-5.6.2.8 The coat/develop system is likely to have several more IPFs defined essentially in the same manner as IPF1 and IPF2, shown above.

R1-5.7 *Unscheduled Downtime versus Total Downtime* — In order to make a distinction between unscheduled downtime and total downtime for an IPF, the IPF function discussed thus far shall be executed twice: once to determine an unscheduled downtime state and a second time to determine a general downtime state.

R1-5.7.1 The first time the function is executed, each module variable is set to zero if the module is in an unscheduled downtime state and set to one otherwise. If the function evaluates to 0, the IPF is in an unscheduled downtime state. Each contiguous instance of process-flow unscheduled downtime is a process-flow failure. If the function evaluates to 1, the IPF may be in either a general downtime state or an up state.

$$M_{i\text{-}UD} = \left\{ \begin{array}{l} \textit{0, if module i is in an unscheduled down state} \\ \\ \textit{1, otherwise} \end{array} \right\}$$

R1-5.7.2 The second time the function is executed, each module variable is set to zero if the module is in either a scheduled downtime state ***OR*** an unscheduled downtime state and set to one otherwise. If the function evaluates to 0, the IPF is in a general downtime state. If the function evaluates to 1, the IPF is a neutral state.

$$M_{i\text{-}GD} = \left\{ \begin{array}{l} \textit{0, if module i is in scheduled down state} \\ \textit{OR an unscheduled down state} \\ \\ \textit{1, otherwise} \end{array} \right\}$$

R1-5.7.3 To summarize, if IPF(M_{UD}) = 0, the process-flow state is *unscheduled downtime (UD)*. Otherwise, if IPF(M_{GD}) = 0 the process-flow state is *general downtime (GD)*, and if IPF(M_{GD}) = 1, the IPF state is *uptime*.

NOTE 8: The process-flow state for an IPF that has at least one module in an unscheduled downtime state may be either (1) unscheduled downtime, (2) general downtime, or (3) neutral. Condition (1) occurs when the unscheduled downtime module is serial within the IPF. Condition (2) occurs when the unscheduled downtime module is not serial within the IPF, but a module (or set of modules) that is serial within the IPF is in a scheduled downtime state. Condition (3) occurs when none of the downtime modules are serial within the IPF regardless of being in a scheduled or unscheduled state.

R1-6 Determining Multi-Path Cluster Tool States

R1-6.1 The temporal mapping rules for determining multi-path cluster tool "productive/unscheduled downtime/neutral" states from module "productive/not-productive" states and IPF "up/downtime/unscheduled" states is as follows:

R1-6.1.1 If any module is in the "productive" state, then the cluster tool is in the "productive" state.

R1-6.1.2 Otherwise, if all of the IPFs are in the "unscheduled downtime" state, then the multi-path cluster tool is in the "unscheduled downtime" state.

R1-6.1.3 Otherwise, the multi-path cluster tool is in the "neutral" state.

R1-6.2 Each contiguous instance of a multi-path cluster tool unscheduled downtime state is a multi-path cluster tool failure.

NOTE 9: This logic is similar to the relationship between module states and the equipment states in SEMI E116, where the SEMI E116 "busy" state is analogous to the multi-path cluster tool "productive state," the SEMI E116 "blocked" state is analogous to the "unscheduled downtime" state, and the SEMI E116 "idle" state is analogous to the "neutral" state. However, the actual relationship between these two sets of states is neither trivial, nor direct.

NOTE 10: Productive time may not be easily allocated to IPFs in the general case. It is expected that some modules will belong to more than one IPF and that it will be prohibitive to ascertain the specific flow for each module from moment to moment. Hence, metrics that depend on productive time may not be calculated for IPFs.

NOTE 11: For the metrics presented in this document, it is not necessary to calculate downtime states other than unscheduled downtime at the multi-path cluster tool level. The effect of states other than productive and unscheduled downtime on the multi-path cluster tool is evaluated as the aggregate effect of such states on the IPFs.

R1-6.3 *Example 3* — A simplified example with a discrete timeline is shown in Figure R1-12. In this example there are three modules (i.e., M1, M2, M3) and three IPFs (i.e., IPF1, IPF2, IPF3). IPF1 uses all three modules, whereas IPF2 does not use M3, and IPF3 does not use M2. The state value functions for the IPFs are IPF1 = M1 × M2 × M3, IPF2 = M1 × M2, and IPF3 = M1 × M3, respectively. Temporal mapping of the IPFs and the multi-path cluster tool is described in Table R1-4.

NOTE 12: The condition between time t = 4 and t = 5, where the multi-path cluster tool is productive but all of its IPFs are down, is expected only as a transient condition in actual practice. Once the productive module finishes its task in progress, the multi-path cluster tool would be expected to go down. However, while the module is productive, it also is accruing theoretical processing time used in the SEMI E79 metric, rate efficiency. The allocation of this transient condition to productive time is necessary in order to guarantee that rate efficiency evaluated over any interval is never greater than 100%.

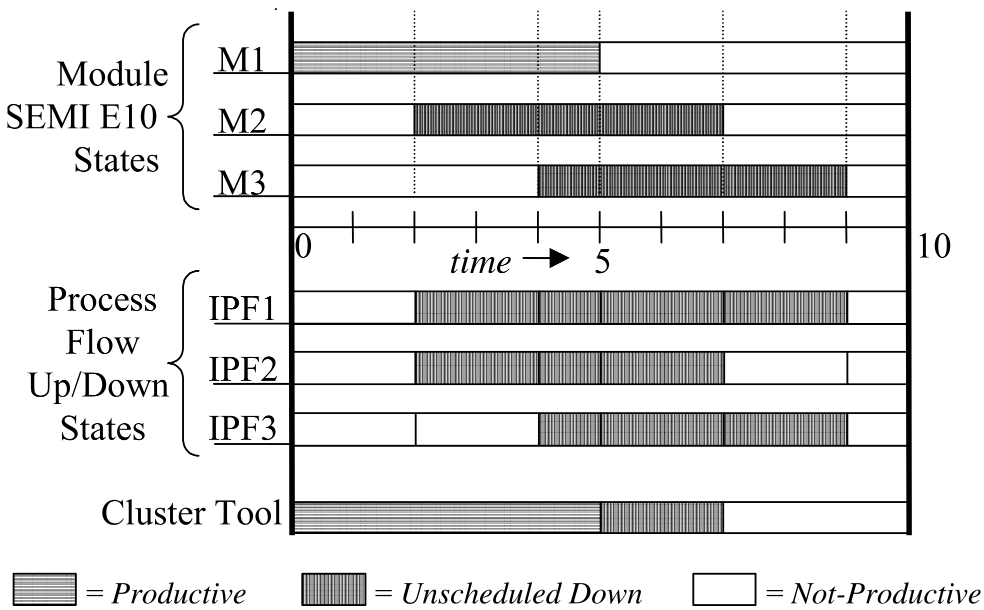


Figure R1-12
Mapping Cluster-Tool States, Example 3

Table R1-4 Temporal Mapping of Example 3

Time	*Module Events*	*IPF Events*	*Cluster Tool State*
t = 0	M1 is productive.	All IPFs are up.	Productive
t = 2	M2 goes down. M1 is still productive.	IPF1 and IPF2 go to unscheduled downtime.	Productive
t = 4	M3 goes down. M1 is still productive.	All IPFs are in unscheduled downtime.	Productive
t = 5	M1 exits productive state. No modules are productive.	All IPFs are still in unscheduled downtime.	Unscheduled Downtime
t = 7	M2 come back up. M3 transitions into scheduled downtime.	IPF2 is up. At least one IPF is up. IPF1 and IPF3 are down, but not in unscheduled downtime	Neutral
t = 9	M3 comes back up. All modules are up.	All IPFs are up.	Neutral

R1-7 Intended Process-Flow and Multi-Path Cluster-Tool Metrics

R1-7.1 Once the IPF and multi-path cluster tool state histories have been prepared, evaluation of metrics may be performed in a similar manner to that used for evaluating non-cluster or single-path cluster tools or modules. The metrics are defined below with sample calculations based on Example 3 from Section R1-6.

NOTE 13: The multi-path cluster tool metrics presented here reflect the reliability of the multi-path cluster tool against total failure rather than partial failure. It is recognized that these metrics proposed here will reflect more favorably on systems with higher levels of redundancy at each process step. The cost or "trade-off" of this redundancy may be evaluated using other metrics from SEMI E10, SEMI E79, SEMI E35, or from non-standard evaluations. It also is recognized that these metrics will not reflect the partial loss of throughput for an IPF that is "up," but some of its alternative modules are "down." Once again the analyst is encouraged to consult other metrics from SEMI E10, SEMI E79, or from non-standard evaluations.

R1-7.2 *Multi-Path Cluster Tool Reliability*

R1-7.2.1 *Multi-Path Cluster Tool Mean Productive Time Between Failure ($MTBF_{p\text{-}CT}$)* — mean productive time between failure where productive time occurs when at least one module is in the productive state, and a failure occurs when there are no available IPFs through the multi-path cluster tool due to module-level unscheduled downtime.

$$MTBF_{p\text{-}CT} = \frac{\text{Multi–Path Cluster Tool Productive Time}}{\text{Number of Multi–Path Cluster Tool Failures}}$$

$$= \frac{5 \text{ hours}}{1 \text{ failure}}$$

$$= 5 \text{ hours}$$

R1-7.2.2 *Multi-Path Cluster Tool Failure Time (MFT_{CT})* — mean time when there are no available IPFs through the multi-path cluster tool due to module-level unscheduled downtime.

$$MFT_{CT} = \frac{\text{Multi–Path Cluster Tool Unscheduled Downtime}}{\text{Number of Multi–Path Cluster Tool Failures}}$$

$$= \frac{2 \text{ hours}}{1 \text{ failure}}$$

$$= 2 \text{ hours}$$

NOTE 14: Since multi-path cluster tool productive time and multi-path cluster tool unscheduled downtime are mutually exclusive; they may be compatible with approaches based on renewal cycle models. Other renewal cycle results (e.g., the limiting probability of finding the cluster-tool productive or failed when approaching it at random) similarly may apply, as determined by the analyst.

R1-7.3 *Multi-Path Cluster Tool Availability*

R1-7.3.1 *Multi-Path Cluster Tool Aggregate IPF Uptime ($Uptime_{CT\text{-}IPF}$)* — availability of the multi-path cluster tool as a function of module "up/downtime/unscheduled downtime" states and is evaluated as the aggregate uptimes of all IPFs.

$$Uptime_{\ CT\text{-}IPF} = \frac{\sum_{all\ IPFs} IPF\ Uptime}{\sum_{all\ IPFs} IPF\ Operations\ Time} \times 100$$

$$= \frac{3+5+5}{10+10+10} \times 100$$

$$= \frac{13}{30} \times 100$$

$$\approx 43.3\%$$

NOTE 15: For reference, the value of the aggregate availability efficiency metric from SEMI E79 for the same example is 20/30 or 66.7%. This difference clearly demonstrates that depending on which combination of modules is "down," the effect on the multi-path cluster tool's availability may be substantially different than the aggregate module availability.