17

NLC Reliability Considerations

Contents

17.1 Goals

The SLC operates with an overall accelerator availability of about 80% [Erickson 1995]. The NLC will be nearly ten times as large and consume approximately six times the power of the SLC. Simple scaling of the SLC fault rates to the NLC results in an NLC which is effectively never operational. It is important that the issues of NLC availability be addressed from the onset of the design and engineering process so that the required component and system reliabilities are achieved. The goals of this chapter are threefold:

1. Establish an availability/reliability specification for the NLC on a machine basis (e^- injector, damping ring, main linac, etc.) and on a system basis (power supplies, magnets, klystrons, etc.). These specifications are arbitrary by nature but are to be compared, as far as possible, with the operational experience of existing accelerator complexes. An availability target of 85% for the full NLC has been adopted.

2. Develop a formal solution to the problem of how availability/reliability is to be accomplished. This requires shifting the responsibility for availability/reliability from a separate and detached upper-level oversight management team to those who are responsible for system development, engineering, implementation, and maintenance. In order to succeed, the concepts of reliability and availability need to be integral to the systems development and must receive necessary resources through a bottoms-up approach with top-down support and review.

3. Identify where reliability engineering effort should be initiated because of discrepancies between performance requirements and known behavior, in those areas where information is lacking, and where exorbitant costs are projected.

17.2 Reliability and Availability

Reliability is the probability that an item or system will perform the necessary function without failure for a given period of time. Reliability, $R(t)$, is characterized by the mean time to failure, $MTTF$. For a system of N_s identical components, the $MTTF$ of the system is taken to be $MTTF_i/N_s$ where $MTTF_i$ is the mean time to failure of an individual component. For the case of constant failure rate λ,

$$\lambda = (MTTF)^{-1} \tag{17.1}$$

and

$$R(t) = e^{-\lambda t} \tag{17.2}$$

A more reliable system thus lasts longer between repairs than a less reliable system.

Availability is the probability that a repairable system will be available for use when required. Availability for the NLC is defined as A,

$$A = 1 - MTTR/MTTF \tag{17.3}$$

wherein $MTTR$ is the mean time to recover which is the average repair time plus accelerator operations recovery time. In general, system availability is enhanced by high reliability and short repair and recovery times. The definition 17.3 is adopted for the NLC accelerator as representative of a complex system in which additional components continue to fail during the time in which recovery is being made for a previous fault. To show how availability of the NLC can vary with respect to that of the SLC, Eq. 17.3 is plotted in Figure 17-1 over a range of $MTTF$, normalized by the $MTTF$ of the SLC ($MTTF/MTTF_{\rm slc}$), for several values of $MTTR$, again normalized by the $MTTR$ of the SLC ($MTTR/MTTR_{\rm slc}$). In Figure 17-1 it is seen that the availability is increased by reducing the $MTTR$ or

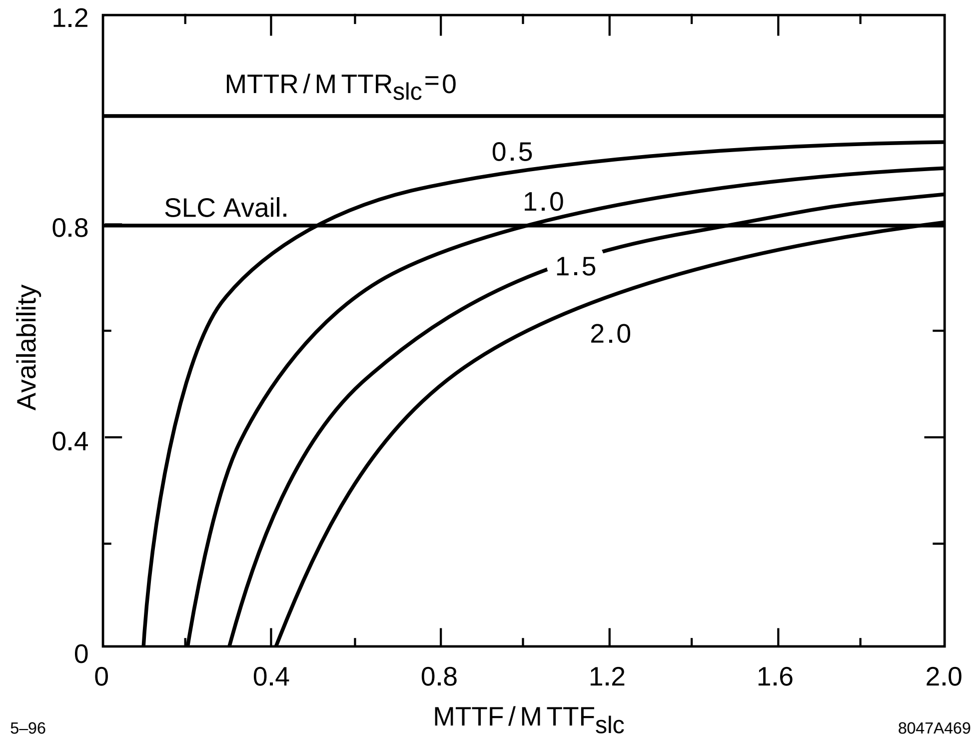

Figure 17-1. *Availability vs.* $MTTF/MTTF_{\rm slc}$ *for various values of* $MTTR/MTTR_{\rm slc}$ *.*

alternatively increasing the $MTTF$ for a given $MTTR$. If the $MTTF$ in the NLC equals that of the SLC (albeit the increased number of NLC components) while the $MTTR$ increases by a factor of two due to say travel time, the availability drops to 60% compared with the value of about 80% for the SLC. Also from Figure 17-1 it is seen that if the $MTTR$ exceeds the $MTTF$, availability drops to zero. This has been the experience with SLC operations.

When discussing system performance, reliability is most often used as a figure of merit. For the machines which comprise the systems, availability is the appropriate figure of merit. As noted above, availability can be enhanced through high reliability. Fortunately, availability can also be improved through reduced repair and recovery times and through component redundancy.

17.3 Target NLC Availability

A target of 85% NLC availability over a scheduled running cycle of 6500 hours is assumed. This is a running period of nine months on and three months off in a calendar year. Numerous short maintenance and repair periods erode the time allocated for machine operations. One-shift-per-week maintenance is a 5% cost to operation. In a strict accounting view, one shift per week of scheduled maintenance during the nine-month cycle leaves only 10% of the time to be allocated to unscheduled outage, from all causes. Experience at SLAC indicates that with the exception of some of the utility installations, very few of the accelerator components have a preventive maintenance program which require scheduled outage during a nine-month cycle. Most, if not all, scheduled maintenance tasks can be accomplished during an annual three-month down. The bulk of the eight-hour scheduled outages taken during a running cycle are used to accomplish remedial repair tasks which have accumulated during the period since the previous outage. These are most appropriately charged to unscheduled downtime.

It appears to be a straightforward task to design an NLC which has minimum maintenance requiring scheduled outages. The incremental cost to accomplish this is minimal given that so little of the present accelerator systems (both at SLAC and at other accelerator laboratories) have scheduled maintenance requirements. It is important, however, to identify those components which presently require periodic outages for maintenance and to reduce such requirements through judicious design and configuration modifications.

17.4 NLC Machine Availability and System Reliability

A proposed NLC availability specification has been developed for the NLC machines and systems for 85% availability over 6500 hours per year of scheduled operations. To develop this specification, the NLC has been divided into 12 machines: e^- source and linac, e^- damping ring and first compressor, e^- booster linac and second-stage compression, e^- main linac, e^- final focus and dumpline, and an identical breakout for the positron complex with the addition of the e^+ source and linac and e^+ pre-damping ring. Similarly, the NLC has also been divided into eight categories of systems: power supplies, magnets, klystrons, modulators, etc. When divided in the same fashion, the SLC consists of six distinct machines, each of similar complexity as an NLC counterpart; the SLC has the same eight categories of systems but with fewer components per system. The overall product of NLC machine availabilities is 85%; the overall product of the NLC system availabilities is 85%. A mean time to recover ($MTTR_s$) of one hour has been chosen for the systems. Equal weighting for each of the machines has been assumed except for the cases of the main linacs which are each given three times the weighting of the other machines. Table 17-1 lists the proposed availability specification for the various NLC machines and the assumed weighting factors. In Table 17-1 the listed availability is simply A_m,

$$A_m = 0.85^{w_m/16} \quad , \tag{17.4}$$

wherein w_m is the weight factor for a given machine, 16 is the sum of the 12 weight factors, and 0.85 is the target availability for the full NLC. Table 17-2 lists the proposed availability specifications for NLC systems. For the noted assumed $MTTR_s$, the required $MTTF_s$ for the system as a whole is given by

$$MTTF_s = MTTR_s / (1 - A_s) \tag{17.5}$$

where A_s is the listed system availability. For Tables 17-1 and 17-2, the allowed unscheduled outage is based on an assumed 6500 hours per cycle of scheduled operating time. Given the $MTTF_s$ for a system, the corresponding required $MTTF_i$ for an individual component is noted in Eq. 17.5.

Each of the 12 machines must be available 99% of the time (97% for the main linacs) in order to achieve the 85% availability goal. For a scheduled operating cycle of 6500 hours this allows for 66 hours of outage per machine per cycle (195 hours for each of the main linacs) The subtotal outage for the e^+ machines is greater than that of the e^- machines because of the added complexity of a positron production system and pre-damping ring.

A preliminary specification of NLC component reliability has been developed. The minimum $MTTF_i$ of the components which is needed to achieve the system availability specification is given by

$$MTTF_i = N_s MTTR_s / (1 - A_s) \tag{17.6}$$

wherein N_s is the number of identical components in a system, $MTTR_s$ is the mean time to recover of the particular system, and A_s is the specified availability for the system. As an example, for N_s = 1500, $MTTR_s$ = 1 hour, and A_s = 0.995, the required $MTTF_i$ = 300,000 hours.

Scheduled Operating Hours: 6500			
	Weight	Availability	Unscheduled Outage (hours)
e^- Inj, Source and Linac	1	0.99	66
e^- DR and Compressor 1	1	0.99	66
e^- Booster Linac and Comp. 2	1	0.99	66
e^- Main Linac	3	0.97	195
e^- Final Focus and Dumpline	1	0.99	66
Subtotal e^- machines:	**7**	**1**	**458**
e^- Inj, Source and Linac	1	0.99	66
e^+ Source and Linac	1	0.99	66
e^+ Pre-damping Ring	1	0.99	66
e^+ DR and Compressor 1	1	0.99	66
e^+ Booster Linac and Comp. 2	1	0.99	66
e^+ Main Linac	3	0.97	66
e^+ Final Focus and Dumpline	1	0.99	66
Subtotal e^+ machines:	**9**	**1**	**589**
Totals:	**16**	**0.85**	**1047**

Table 17-1. *Availability specifications for the NLC machines.*

NLC Systems	Availability	$MTTR_s$ (hours)	$MTTF_s$ (hours)	Unscheduled Outage (hours)
Power Supplies	0.975	1	40	163
Magnets	0.975	1	40	163
RF Systems	0.950	1	20	325
Motors	0.975	1	40	163
BPMs	0.990	1	100	65
Controls	0.985	1	67	98
Utilities	0.995	12	2400	33
Miscellaneous	0.995	1	200	33
Totals:	**0.85**			**1040**

Table 17-2. *Availability specification for the NLC systems.*

SLC machine and system availabilities and component $MTTF_i$ have been compiled for the 1992, 1993, and 1994/1995 SLC operating cycles. Operating experience of SLAC systems compares favorably with experience at Fermilab, CERN, KEK Photon Factory, Cornell, APS, and AGS. Table 17-3 lists the accelerator availabilities for physics of these various laboratories; the running cycles are noted. In general it was found that the same sorts of problems exist at all the labs. When the lengths of the running cycles are considered along with the sizes of the various machines and the peculiarities of the various accounting methods, the performance of the different accelerators are quite similar. Some labs do better with certain technologies than others but there are no clear differences on the whole. Because of the apparent similarities between the labs, it has been decided to base NLC technology expectations on SLAC experience, since the details of the SLAC data are more readily available at SLAC. It is important however to make comparisons with the other labs on a case-by-case basis when anomalies or uncertainties occur. On average, the six SLC machines (injector, two damping rings with compressor systems, e^+ source, linac, and arcs and final focus) each had an availability of approximately 97%.

Table 17-4 lists a preliminary parts count for the NLC. This information was taken from the NLC ZDR WBS [NLC WBS 1996]. For comparison purposes, Table 17-5 lists a parts count for the SLC. The data in Table 17-5 was gathered by counting entries in the SLC control system database. Initial counts of the numbers of NLC components indicate that there is about a factor of ten more components of all types in the NLC compared to a similar count of SLC components. Attention must be paid to improving the performance of NLC systems over that which is being achieved in existing systems of similar complexity.

17.5 A Formal Solution

Achievement of the specified NLC availability comes through the integration of the system and machine availability/reliability specifications into the component, system, and machine-functional specifications at the onset of the engineering design phase. Performance specifications of individual components will include the specification of reliability. The design review process must include attention to the availability/reliability requirements. A precision supply that never works is no better than an out-of-tolerance supply that never fails. Within a machine the availability budget must be respected. This task is best done at the engineering level but must be managed in the same fashion and at the same time that the more familiar performance criteria are managed.

Reliability engineering is a recognized discipline which plays an important role in all technologically-oriented industries (*e.g.*, semiconductor, aeronautics and astronautics, automotive, telecommunications, and power industries). There are a number of professional societies dedicated to developing the techniques and methodologies of reliability (*e.g.*, IEEE Reliability Society, Society of Automotive Engineers, Society of Reliability Engineers, Society of Logistic Engineers, American Institute of Aeronautics and Astronautics [RS IEEE, SAE, SRE, SLE, AIAA]). There are numerous annual meetings of these societies wherein tutorials on these methods are given in addition to the familiar conference presentations of topical issues (the Annual Reliability and Maintainability Symposium [ARMS 1996], for example). There are a large number of textbooks and courses on availability [Lewis 1996, O'Connor 1985]. It is important to take advantage of the tools developed and to apply them to the issues of NLC reliability. It is also necessary to understand the lessons learned in areas other than accelerators and to apply these lessons to the problems facing NLC construction. In many cases, the detailed solutions of how reliability in a Boeing 777 is achieved are not directly applicable to the NLC, but the thought processes going into developing a Boeing 777 are identical to what is required to successfully meet the NLC reliability goals.

For the NLC CDR, it is important that the issues associated with component reliability and system availability be fully integrated into the component and system engineering. Segregation of the discussion of availability into a separate chapter (in the CDR) will not fulfill the need to infuse the requirement for reliability beginning at the most basic levels of NLC design. If availability is to be achieved for a system which is nearly ten times larger than what has previously

Laboratory	Availability	Reference
ANL (APS) 95	68.30%	Argonne National Lab., Private Communication, Site Visit – R. Gerig, D. Ciarlette
CERN (SPS) 94	69.30%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 93	72.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 92	74.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 91	72.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 90	74.00%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
CERN (SPS) 89	71.20%	1994 SPS & LEP Machine Statistics CERN SL / Note 95–15 (OP) M. Colin, G. Cultrut and B. Desforges
Fermi 91	72.64%	Fermi Accelerator System Tally Sheets, Site Visit – R. Mau
Fermi 92	65.86%	Fermi Acclerator System Tally Sheets, Site Visit – R. Mau
Fermi 93–94	63.71%	Fermi Acclerator System Tally Sheets, Site Visit – R. Mau
Fermi 93–94	63.71%	Fermi Acclerator System Tally Sheets, Site Visit – R. Mau
SLAC (SLC) 92	81.00%	1992 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (SLC) 93	84.53%	1993 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (SLC) 95	80.87%	1994/95 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (ESA) 92	87.01%	1992 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (ESA) 93	93.25%	1993 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC (ESA) 94	93.33%	1994 SLC Revealed Failure Tables, Internal SLAC Memo – W. Linebarger
SLAC SSRL 94	97.04%	SSRL, Private Communication, Site Visit – E. Guerra
SLAC SSRL 95	96.60%	SSRL, Private Communication, Site Visit – E. Guerra
AGS, FY95Q3	86.30%	Brookhaven National Lab, FY 95 3rd Qtr. Report – F. Weng
AGS, FY94Q4	86.70%	Brookhaven National Lab, FY 94 4th Qtr. Report – F. Weng
Cornell 91–92	74.10%	CESR Reliability Summary FY 1992–FY 1994 – D. Rice
Cornell 92–93	77.90%	CESR Reliability Summary FY 1993–FY 1994 – D. Rice
Cornell 93–94	84.00%	CESR Reliability Summary FY 1994–FY 1994 – D. Rice
KEK Photon Factory Linac 10/92–9/93	98.70%	KEK Operations Report FY 1992–FY 1993
KEK Photon Factory Linac 10/91–9/92	98.40%	KEK Operations Report FY 1991–FY 1992
KEK Photon Factory Linac 10/90–9/91	97.70%	KEK Operations Report FY 1990–FY 1991

Table 17-3. *Availabilities of several accelerator laboratories.*

	Pwr sup	Magnets	Klystrons	Modulators	Motors	BPMs	**Sys. Total**
e^- Inj, Source and Linac	245	229	16	16	0	381	**887**
e^- DR and Compressor 1	817	709	5	5	300	555	**2391**
e^- Booster Linac and Comp. 2	452	482	116	116	1077	291	**2534**
e^- Main Linac	736	756	2264	1132	14643	5300	**24831**
e^- Final Focus and Dumpline	871	1466	1	1	1344	472	**4155**
e^- Inj, Source and Linac	244	229	40	40	0	381	**934**
e^+ Source and Linac	236	241	32	32	0	81	**622**
e^+ Pre-damping Ring	700	700	2	2	300	300	**2004**
e^+ DR and Compressor 1	817	709	5	5	300	555	**2391**
e^+ Booster Linac and Comp. 2	452	482	116	116	1077	291	**2534**
e^+ Main Linac	736	756	2264	1132	14643	5300	**24831**
e^+ Final Focus and Dumpline	871	1466	1	1	1344	472	**4155**
NLC Total	**7177**	**8225**	**4862**	**2598**	**35028**	**14379**	**72269**

Table 17-4. *Preliminary NLC parts count for several systems.*

	Pwr sup	Magnets	Klystrons	Modulators	Motors	BPMs	**Sys. Total**
e^- Inj, Source and Linac	249	247	16	16	10	37	**575**
e^- and e^+							
DRs and Compressors	40	456	5	5	6	199	**711**
e^+ Source and Linac	30	452	2	2	5	204	**695**
e^- Main Linac	608	608	242	242	22	283	**2005**
SLC Arcs	119	1000	0	0	912	978	**3009**
SLC Final Focus	192	192	0	0	23	59	**466**
SLC Total	**1238**	**2955**	**265**	**265**	**978**	**1760**	**7461**

Table 17-5. *SLC parts count for several systems.*

been achieved by the accelerator community, reliability must be fully accepted by the engineering and fully supported by the management.

Availability of the systems is based on the reliability of the individual components in concert with component configurations which include considerations of system repairability and redundancy. The solutions are specific to the particular systems; redundancy in the rf systems is a straightforward cost-effective solution, whereas component reliability combined with ease of changeability appears to be the proper solution for many of the magnet power supply applications.

17.6 Three Examples: Klystrons, Power Supplies, and Motors

In the main linacs, the expected $MTTF_i$ of the klystrons is 20,000 hours [Caryotakis 1995] and the $MTTF_i$ of the thyratrons is 10,000 hours [Wait 1996] Given an estimated count of 4000 klystrons and 2000 thyratrons in the NLC, approximately 1300 of each will fail and need replacement every cycle; this is a combined failure rate of one klystron or modulator every 2.5 hours. In order to operate the machines, on-line redundancy is required. By necessity, the repair rate must be equal to or faster than the failure rate. Therefore, the availability for the rf system is simply A_{rf}

$$A_{rf} = 1 - e^{-1}/n! \tag{17.7}$$

where n is the number of redundant rf modules available for use when needed. For $n = 6$, $A_{rf} = 0.9995$. Present plans call for 3% redundancy in the number of rf modules which is quite sufficient. The rf systems are an operating cost issue but not so much one of availability. It is important to work to extend the $MTTF_i$ of the klystrons and thyratrons so as to reduce the cost of these consumables. It is worth noting, that effort must go into developing reliable waveguide valves to permit changing to klystrons during accelerator operations and to design the modulators such that the thyratrons can be easily changed.

There are approximately 750 quadrupoles per main linacs. The power supplies for these magnets are expected to be in the power range of a few kilowatts each. For the pair of linacs, the $MTTF_i$ of the power supplies is 300,000 hours to give system availability of 0.995, assuming the nominal one-hour $MTTR_s$. Should the $MTTR_s$ increase to two hours due to travel time or complexity of changing, the $MTTF_i$ increases to 600,000 hours. Rack-mounted power supplies in this power range used at SLAC have an $MTTF_i$ of about 300,000 hours [Donaldson 1996] and an $MTTR_i$ of about 1.5 hours. Whereas the present performance of similar power supplies meet the NLC goals, care must be taken to keep the $MTTR_s$ of less than one hour.

There are approximately 35,000 motors in the quadrupole and structure mover systems of the two NLC linacs. Since a stuck mover is a "soft" failure that contributes to emittance growth but does not stop the machine dead, it has been decided to allow 1% of the motors to fail each month before stopping to fix the accumulated failures. A failure rate of 1% per month corresponds to a $MTTF_i$ of 8.3 years. Motor manufacturers claim $MTTF_i$s of five to seven years for 100% duty factor usage and seven-to-ten-year $MTTF_i$ for 50% duty factor usage [Parker 1996, Warner 1996]. SLC experience has been quite good with motors. However, it will be important to design the movers with motor replaceability in mind since 1% per month failure rate is 3500 failures per year and the $MTTR_i$ needs to be small (on average 350 motors need to be replaced each month during a "short" machine access).

17.7 Summary

Simple scaling of the SLC fault rates to the NLC results in an NLC which is not operational. Reliability and availability need to be fully integrated into the functional requirements of the NLC. Reliability and availability must be explicit at the component, system, and machine levels in the CDR as a natural and normal part of the accelerator design. Real consideration and effort must be dedicated to defining and solving the reliability issues. The solutions to these issues necessarily arise from the engineering teams charged with building the systems. There exist significant engineering disciplines dedicated to addressing the issues, but care needs to be taken such that the correct solutions are properly applied to the relevant problems.

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[SAE] Society of Automotive Engineers Inc., 400 Commonwealth Dr., Warrendale PA 15096-001 USA.

[SLE] Society of Logistic Engineers, 8100 Professional Place, Suite 211, Hyattsville MD 20785-2225 USA.

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Contributors

- C.W. Corvin
- A.R. Donaldson
- J.W. Humphrey
- W.A. Linebarger
- M.H. Munro
- A. Saab
- J.C. Sheppard