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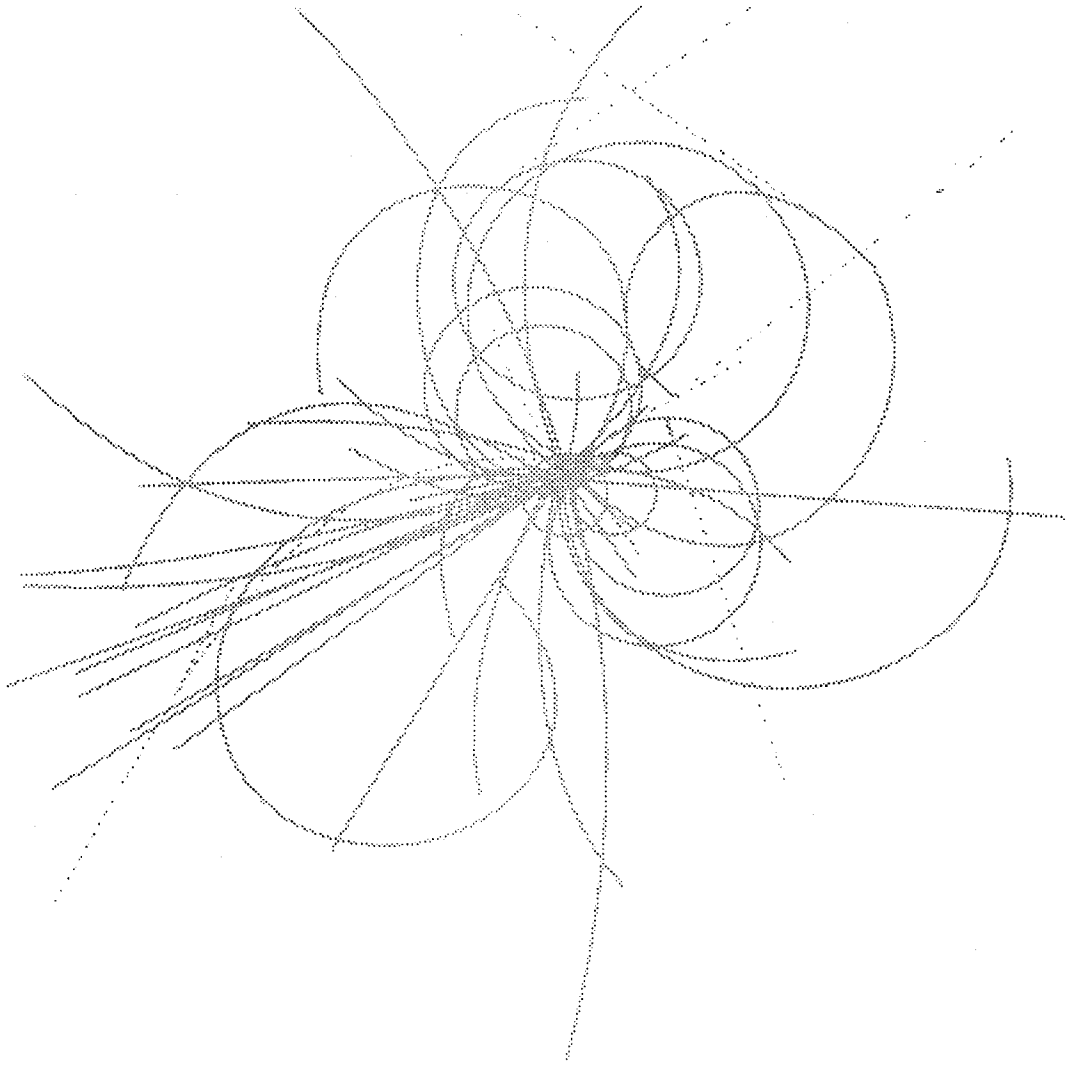
Superconducting Super Collider Laboratory



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March 1991

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

SSCL-376

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

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

SSC ACCELERATOR AVAILABILITY ALLOCATION

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Abstract: Superconducting Super Collider (SSC) operational availability is an area of major concern, judged by the Central Design Group to present such risk that use of modern engineering tools would be essential to program success. Experience has shown that as accelerator beam availability falls below about 80%, efficiency of physics experiments degrades rapidly due to inability to maintain adequate coincident accelerator and detector operation. For this reason, the SSC availability goal has been set at 80%, even though the Fermi National Accelerator Laboratory accelerator, with a fraction of the SSC's complexity, has only recently approached that level. This paper describes the allocation of the top-level goal to part-level reliability and maintainability requirements, and it gives the results of parameter sensitivity studies designed to help identify the best approach to achieve the needed system availability within funding and schedule constraints.

OVERVIEW

A systematic approach to achievement of 80% availability of the Superconducting Super Collider (SSC) accelerator requires equitable apportionment of the allowable downtime among the accelerator subsystems, followed by subdivision of the subsystem allowances to the level at which design alternatives can be selected to arrive at a design choice satisfying the allocation. The approach used to allocate the system-level availability requirement to design-level reliability and maintainability requirements is summarized.

Using current requirements and available information, preliminary availability allocation to the segment level has been completed. The collider segment allocation has been allocated to the component level, the Magnet System has been allocated to the magnet and interconnect level, and the interconnect requirements have been allocated to the part level. The current allocation allows up to six Magnet System failure intervals per year, satisfying a perceived need to accommodate three collider dipole magnet failures per year, and requires no

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improvement of the Injector Complex availability over Fermi National Accelerator Laboratory (FNAL) experience. When fewer than 3.5 Magnet System failures per year are allocated, the number of short-downtime failures allowed causes excessive time loss in ring fill and tune operations. The remainder of the segments need further analysis to understand the degree of redundancy and any special support provisions required to meet the allocations.

At this stage of development, many assumptions are necessary for completion of the analysis. As the program progresses through detailed design, development, testing, commissioning, and early operations, the assumptions will be refined and then replaced with test/operational data to maintain visibility of availability potential, actual achievement, growth progress, and problem areas needing management attention.

MATHEMATICS, MISSION PROFILE AND BEAM CYCLE

SSC reliability and maintainability requirements are derived from the availability goal stated in the 1986 SSC Conceptual Design Report (CDR):

$$\text{Availability} = \frac{\text{(Scheduled uptime) - (Unscheduled downtime)}}{\text{(Scheduled up-time)}} \geq 0.8.$$

Substitution of

$$\text{Unscheduled downtime} = \frac{\text{Scheduled up-time}}{\text{MTBF}} * \text{MDT}$$

into the Availability expression allows calculation of the mean time between failures (MTBF) requirement, provided the mean downtime (MDT) per failure is known from experience or can be estimated from the steps required. When unscheduled downtime is caused by multiple (i through n) subsystems or items,

$$\text{Unscheduled downtime}_{\text{total}} = \sum_{i=1}^{n} \text{Unscheduled downtime}_i$$

and

$$\text{Availability} = 1 - \sum_{i=1}^{n} (1\text{-Availability})_i$$

Accelerator usage is assumed in the Mission Profile[1] to be continuous, 24 hours per day, seven days per week, nine months per year, with an average of one day per week allowed for scheduled maintenance (to be scheduled only on an as-needed basis) followed by three months of scheduled downtime in which maintenance may be accomplished without affecting system availability. Figure 1 summarizes the average annual Mission Profile time allocations, showing 939 hours allowed for scheduled maintenance and 1126 hours allowed for unscheduled maintenance, leaving a total of 4505 hours available for beam operations. Up to 4 hours per day (751 hours/year) are allowed for operations associated with loading and accelerating the beams, leaving 3754 hours of stable beam time.

Figure 2 shows the assumed standard operating cycle, including the time required for collider ring fill [operating time required of the Injector Complex [LINAC, Low Energy Booster (LEB), Medium Energy Booster (MEB), and High Energy Booster (HEB)], the time required for accelerating/decelerating the beams between 2 and 20 TEV, and the number of cycles required/possible during available operating time. The time requirements are consistent

with the Site-Specific Conceptual Design Report dated July 1990. No time allocation was included for special beam tube vacuum controls or other factors which may be necessary for operation beyond the baseline requirements.

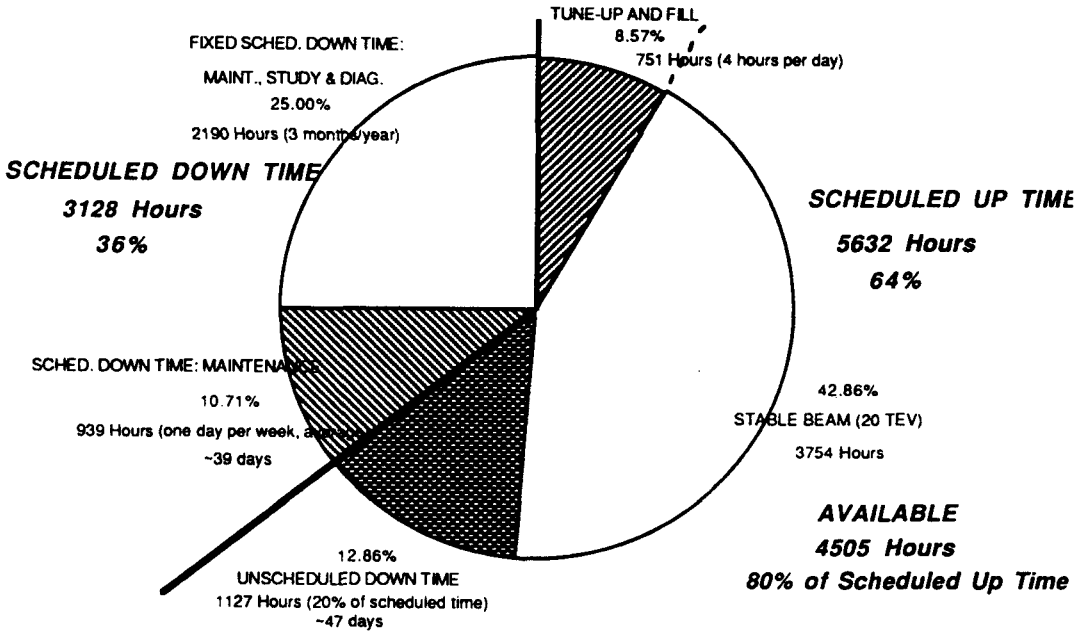
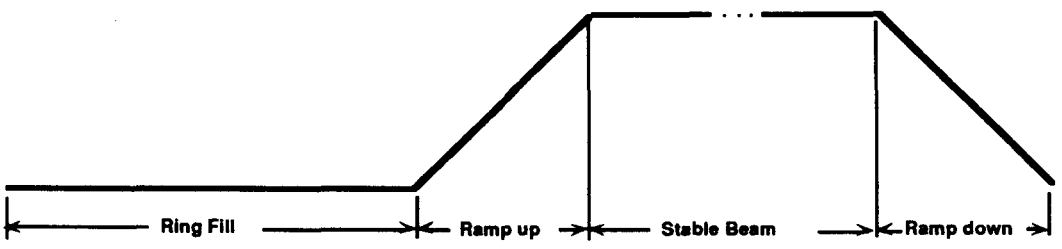


Figure 1. Standard SSC Time Allocation.



Ring Fill = 64 minutes. All SSC Accelerator subsystems must operate.

Ramp up = 25 minutes. Failures in Injector Complex do not affect beams.

Stable Beam = 20 hours, nominal. Failures in Injector Complex do not affect beams.

Ramp down = 25 minutes. Failures in Injector Complex and other subsystems have no effect.

Figure 2. Standard Accelerator Beam Cycle.

ANALYSIS APPROACH

The driving factor in SSC accelerator availability is expected to be the superconducting magnet rings (two Collider and one HEB). For purposes of the allocation, the Magnet System was defined to include all items in the superconducting magnet rings whose maintenance will require warm-up and cool-down of portions of the rings (includes all superconducting magnets, spools, and their interconnection regions). Downtime per failure of these items is estimated to be on the order of 10.5 days, as summarized in Table 1, and there is no feasible possibility of design redundancy. About eight failures (0.032%) per year would consume all the available scheduled and unscheduled downtime.

Table 1. SC Magnet Maintainability Allocation.

MAINTENANCE TASK	DOWN TIME (Hours)	DATA SOURCE
Isolate problem to the faulty magnet	16	CDR
Warm up ring section containing bad magnet	72	SYSTEM SPEC (24 in CDR)
Spoil relevant vacuum	1	CDR
Disconnect bad magnet mechanically	4	FNAL REPORT (4 total
Disconnect bad magnet electrically	4	ESTIMATE in CDR)
Remove bad magnet	2	CDR
Prepare for new magnet, as required	4	CDR
Place new magnet	2	CDR
Align magnet	4	CDR
Connect and check electrically	6	CDR
Connect and check mechanically	6	CDR
Pump down and check for leaks	48	ESTIMATE (36 in CDR)
Hi-pot test	2	CDR
Cooldown	72	SYSTEM SPEC (48 in CDR)
Pre-start checkout	8	CDR
TOTAL Hours	251	CDR + 88 Hours
TOTAL Days	10.5	

It is assumed that most (807 hours of the 939 hours) of the one-day-per-week-as-needed scheduled maintenance will be used for Magnet System replacements. The remaining 132 hours of scheduled maintenance allowance are reserved for possible priority needs such as restoration of critical protection system redundancies. Assuming a Magnet System failure is detected during scheduled operating time, the first 16 hours of downtime time will be used to diagnose and isolate the faulty item and to verify the need to replace it. Once the need has been determined, about ten days of downtime will be scheduled to complete the maintenance. Should the scheduled downtime total reach the 939 hour limit, *all* subsequent downtime for maintenance would be included as unscheduled downtime.

The second area of concern is the Injector Complex, which includes the LINAC, the LEB, the MEB, and the HEB. These subsystems are assumed equivalent, at least from an availability perspective, to the FNAL LINAC, Booster, Main Ring, and Tevatron, respectively. These subsystems are also non-redundant and historically have demonstrated availability lower than the 80% required of the entire SSC Accelerator. Fortunately, these subsystems are required to operate during less than 5% of the standard Accelerator operating cycle. Furthermore, failures during Collider operations generally do not degrade Collider operation, most failures are repaired in less than one hour, and any needed scheduled maintenance may be accomplished during stable Collider operation.

Table 2 shows FNAL statistics for the most recent collider mode operating period. The availability assigned to each Injector Complex subsystem was obtained by adding the unavailabilities associated with the FNAL Utilities, Controls and Miscellaneous "subsystems" to the four primary subsystems in proportion to the unavailability of the primary subsystem.

Table 2. Fermilab Downtime/Availability Summary SSC Availability Comparison.

	# ACTIONS	TOTAL HOURS	MEAN DOWN TIME	AVAIL **	SSC AVAIL	SSC SUBSYSTEM
LINAC	581	110	0.19	0.987	*0.984*	*LINAC* *
BOOSTER	322	66	0.21	0.992	*0.990*	*LEB* *
MAIN RING	454	448	0.99	0.946	*0.935*	*MEB* *
UTILITIES	47	118	2.52	0.986	0.991	COLL. UTIL.
CONTROLS	158	75	0.47	0.991	*0.995*	*GAS*
MISC	45	64	1.42	0.992	0.995	COLL. SAF./INTLK.
TEV INJECTOR TOTAL	1607	881	0.55	0.894		
TEVATRON TOTAL	517	1121	2.17	0.865	*0.891*	*HEB* *
CORRECTORS	46	62	1.35	0.993	0.996	CORRECTOR P.S.
CRYOGENICS	47	75	1.59	0.989	0.994	CRYOGENICS ***
INJECTION	10	16	1.61	0.998	0.999	INJECTION/ABORT
MAGNETS	8	333	41.61	0.960	0.876	MAGNET SYSTEM
MISCELLANEOUS	84	99	1.18	0.988	0.993	MISCELLANEOUS
POWER SUPPLIES	74	134	1.81	0.984	0.990	RING P.S. & REG.
QPM	43	60	1.40	0.993	0.996	QUENCH PROT. SYS.
QUENCH	113	195	1.73	0.976	0.996	MAG. SYS. QUENCHES
RF	47	61	1.31	0.993	0.996	RF SYSTEM
VACUUM	9	30	3.31	0.996	0.998	VACUUM SYSTEM
CEN HE LIQ	4	13	3.19	0.998		
CONTROLS	32	43	1.35	0.995		
TEV/INJ TOTAL	2124	2002	0.94	0.759	0.986	INJECTOR COMPLEX
COLLIDER TOTAL					*0.816*	*COLLIDER*
SSC TOTAL					*0.800*	

* Includes part of Utilities, Controls, and Misc. in proportion to subsystem unavailability

** 1988/89 Collider run scheduled operating time = 8304.00 hours.

*** Includes Central Helium Liquifier

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The remainder of the SSC Accelerator consists of the Collider ring support elements and the Global Accelerator System. Where cost effective, fault tolerance may be designed into these subsystems to achieve high availability. Because these subsystems are analogous to Tevatron support subsystems, availability data from FNAL Tevatron operations were used as a basis for the downtime per failure (one hour additional downtime per failure was assumed necessary and sufficient to account for the larger Collider geographic scale), and as the basis for the relative availability of the Collider subsystems other than the Magnet System. A summary of the pertinent data compared with the SSC Accelerator allocations is included in Table 2.

AVAILABILITY MODEL AND ALLOCATION RESULTS

An allocation model incorporating the above assumptions was developed to calculate the number of failures allowed each Collider subsystem for a given number of Magnet System failures. Each Accelerator failure (other than Injector Complex failures) was assumed to require Collider ring refill plus one full 2-20 TEV magnetic cycle. Failures during ring fill were assumed to require restart of the fill process, averaging a loss of one-half injection cycle per failure. Figure 3 shows the allocated maintenance and fill/tune times, and Table 3 shows these times plus failure counts, availability, and cycle reliability (defined as the probability of operating through a complete Accelerator operating cycle without a failure).

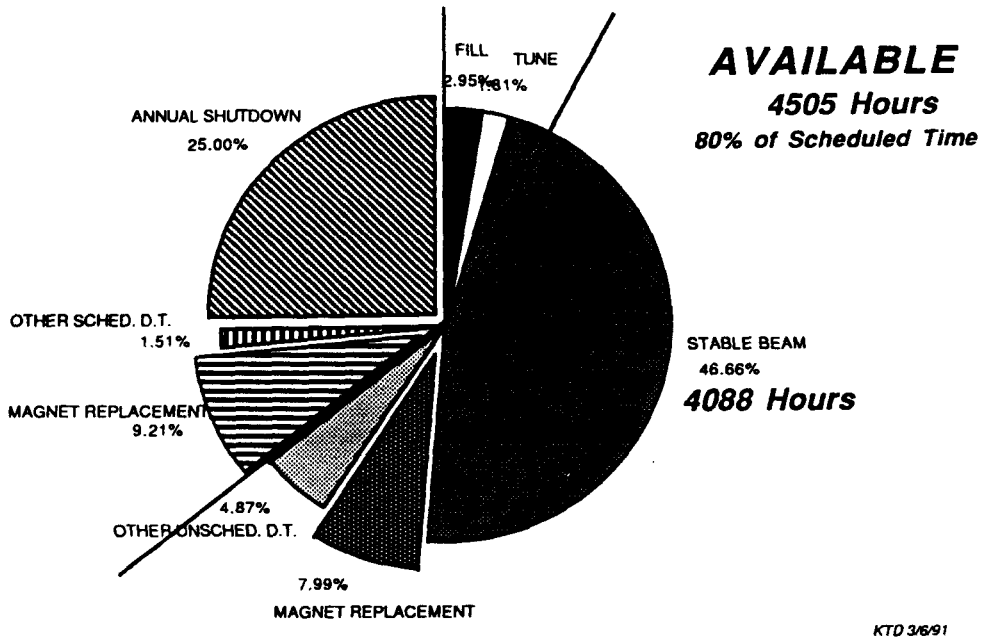

Figure 3. SSC Accelerator Annual Time Allocation.

Figures 4 through 8 show how the above figures of merit vary with the number of magnet failures, with downtime per magnet failure, with the downtime delta due to Collider ring scale, with Injector Complex reliability, and with beam luminosity lifetime. Figures 9.1 through 9.6 show the sensitivity of key figures of merit to the parameters varied in Figures 4 through 8 (reference the appropriate figure for applicable horizontal scale). Because Accelerator availability is a constant for all calculations, non-magnet failure allocations increase rapidly as magnet failure count or downtime per failure decreases. However, as failure count allocations for the short-downtime-per-failure segments increase, cycle reliability falls and time required for ring fill and beam acceleration operations rises. The current goal of no more than four hours per day for beam fill and tune operations limits the allowed number of failures per year to about 450 (consistent with about 3.5 Magnet System failures per year), which is less than the experience data for the Tevatron support subsystems (Table 2). Other goals, like 20 hour nominal stable beam time per beam cycle, place further restrictions on the number of failures allowed (Figure 9.5).

It is anticipated that improved basic reliability, coupled with selective redundancy and scheduled maintenance, will promote achievement of the goals. Figure 10 shows that most of the Tevatron downtime in the reference period was caused by only a few events, hence the major emphasis placed on improved reliability of superconducting magnets. On the short downtime end of the scale are momentary interruptions with a multitude of causes (basically built-in-test errors), and readily isolated hardware failures near the control center where maintenance delay times were minimal. The short-delay types of faults, which would have a greater effect on SSC beam time due to the longer beam restoration process and the wider distribution of the hardware, will be reduced by improved hardware design and quality, improved software techniques, and redundancy where essential.

Table 3. SSC Availability Allocation.

	TUNE/FILL (Hours)		DOWN TIME (Hours)		UNSCHED	#	AVAIL.	CYCLE
	FILL	RAMP	UNSCHED.	SCHED.	DT/FAIL (Hours)	FAILS		REL.
Magnet System R&R	6	5	700	806	16.0	6	.876	.977
Injector Complex	56		63		1	56	.989	.729
*	52	41	17		1	15	.997	.926
Correction P.S.	11	9	25	24	2.3	11	.996	.960
Ring P.S. and Regulators	20	16	54		2.8	19	.990	.930
Quench Protection System	11	8	24	24	2.4	10	.996	.962
Cryogenics	14	11	35	24	2.7	13	.994	.952
Vacuum	3	2	12		4.3	3	.998	.989
Control and Instr. (GAS)	22	17	30	60	1.5	20	.995	.925
RF	11	9	25		2.3	11	.996	.960
Injection/abort	3	2	6		2.6	2	.999	.991
Utilities	14	11	48		3.5	14	.992	.950
Safety and Interlocks	11	9	26		2.4	11	.995	.960
Magnet System Quenches	5	4	22		5.0	4	.996	.983
Miscellaneous	19	15	40		2.2	18	.993	.933
								.582
ACCELERATOR SYSTEM	259	159	1126	939	5.3	213	.800	.393

* FILL and RAMP times for normal cycles without failures.

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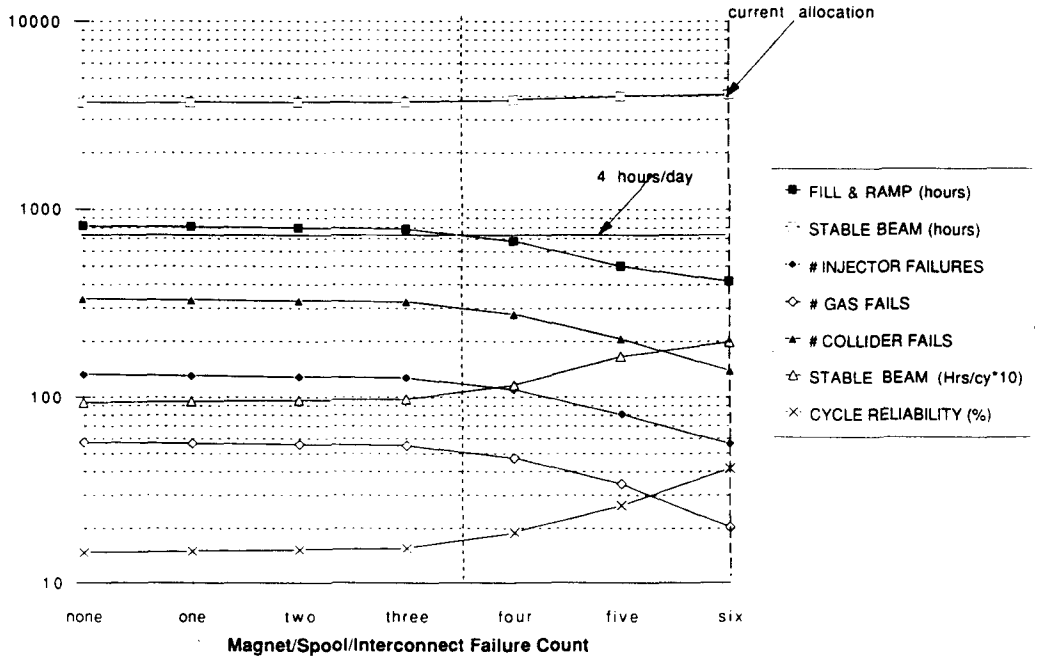

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Figure 4. Parameter Sensitivity to Magnet System Failures.

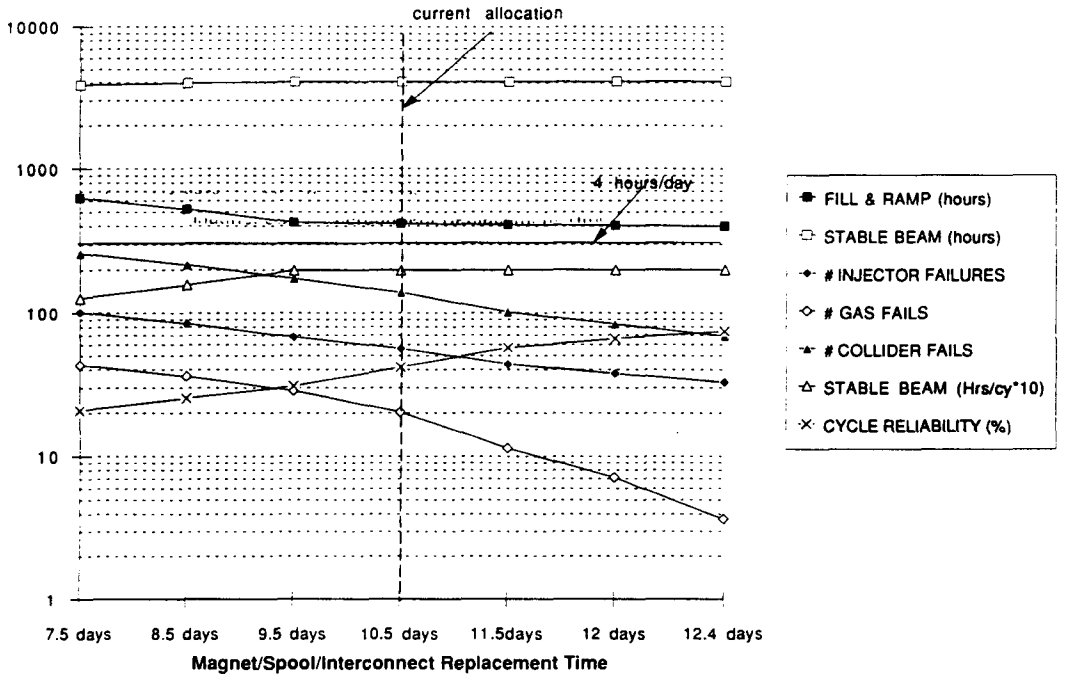

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Figure 5. Parameter Sensitivity to Magnet System Failures.

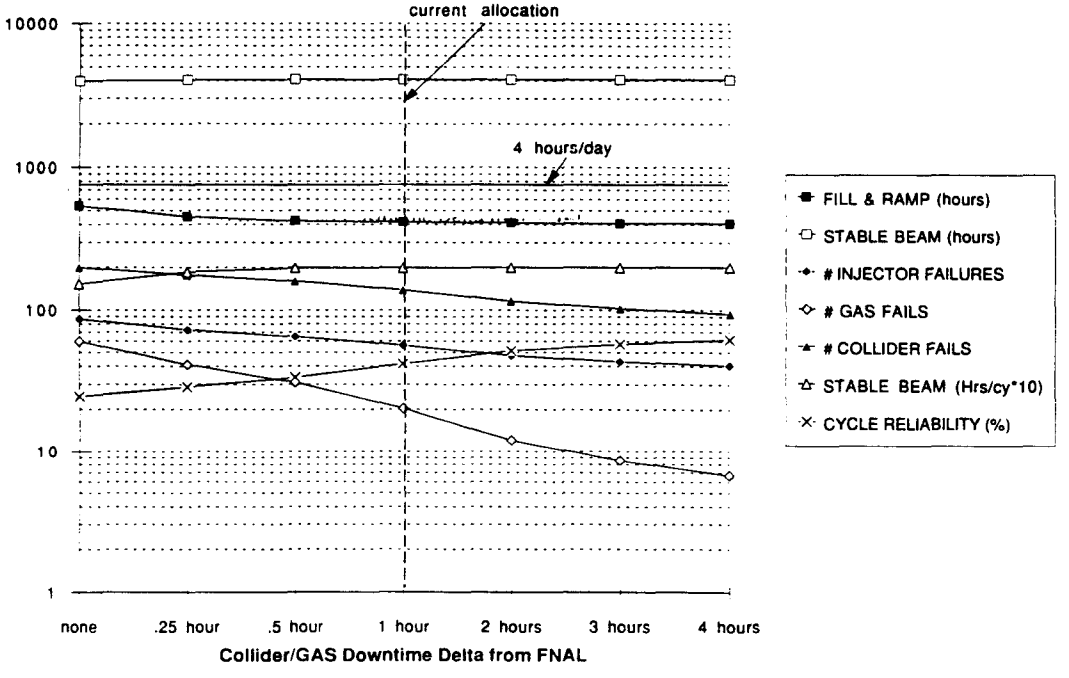

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Figure 6. Parameter Sensitivity to Collider/Gas Downtime.

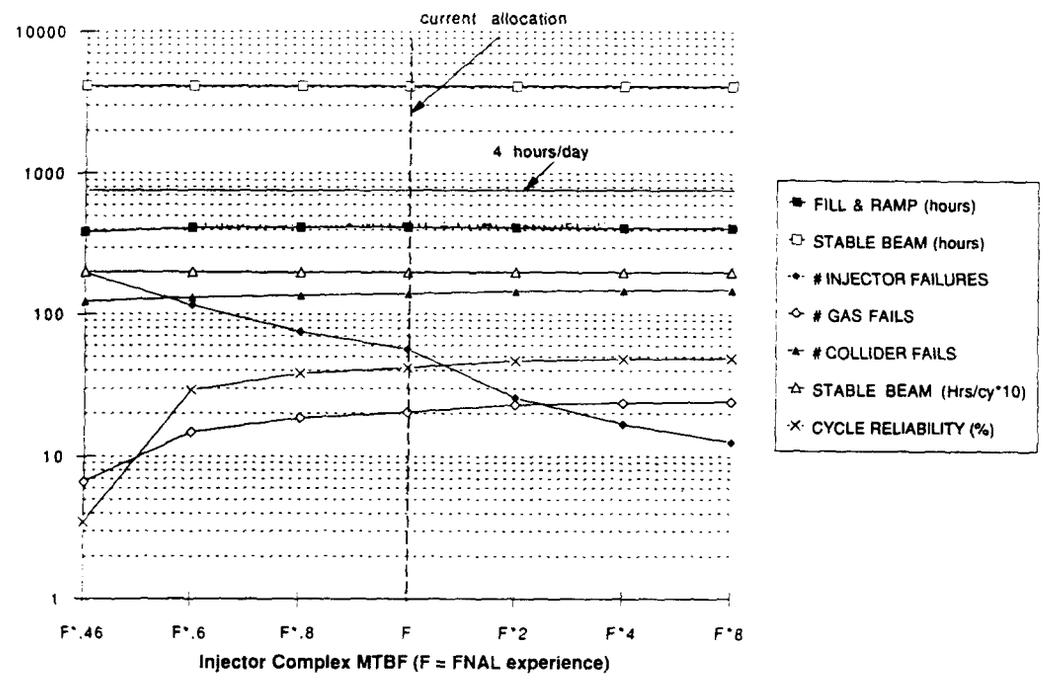

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Figure 7. Parameter Sensitivity to Injector Complex Reliability (MTBF).

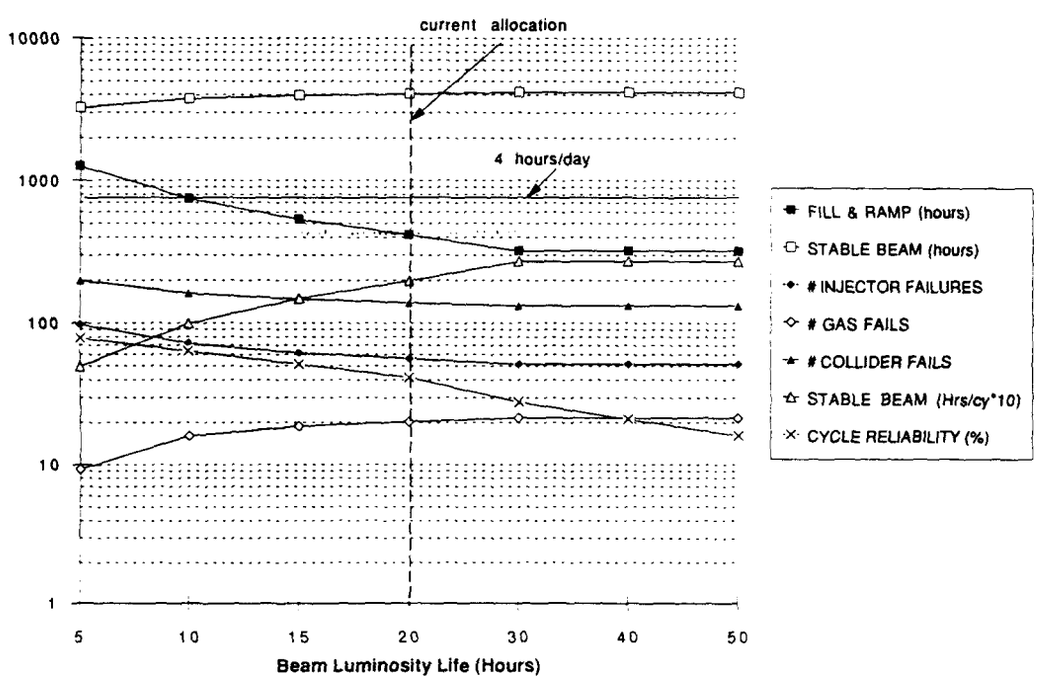

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Figure 8. Parameter Sensitivity TO Beam Luminosity Life.

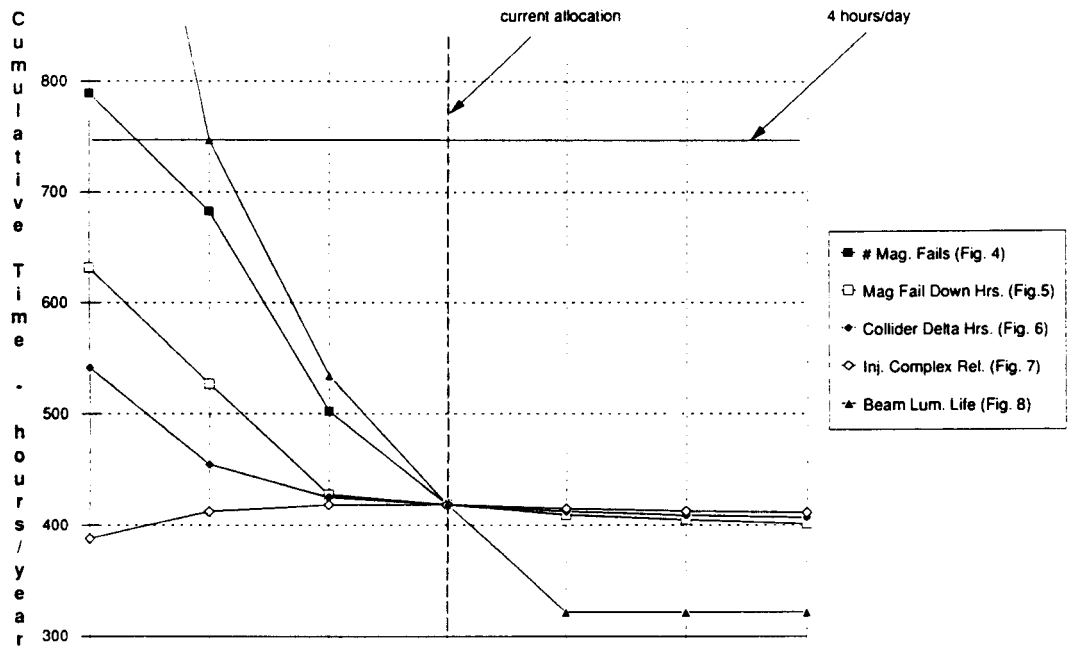

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Figure 9.1. Beam Fill and Tune Time Sensitivity.

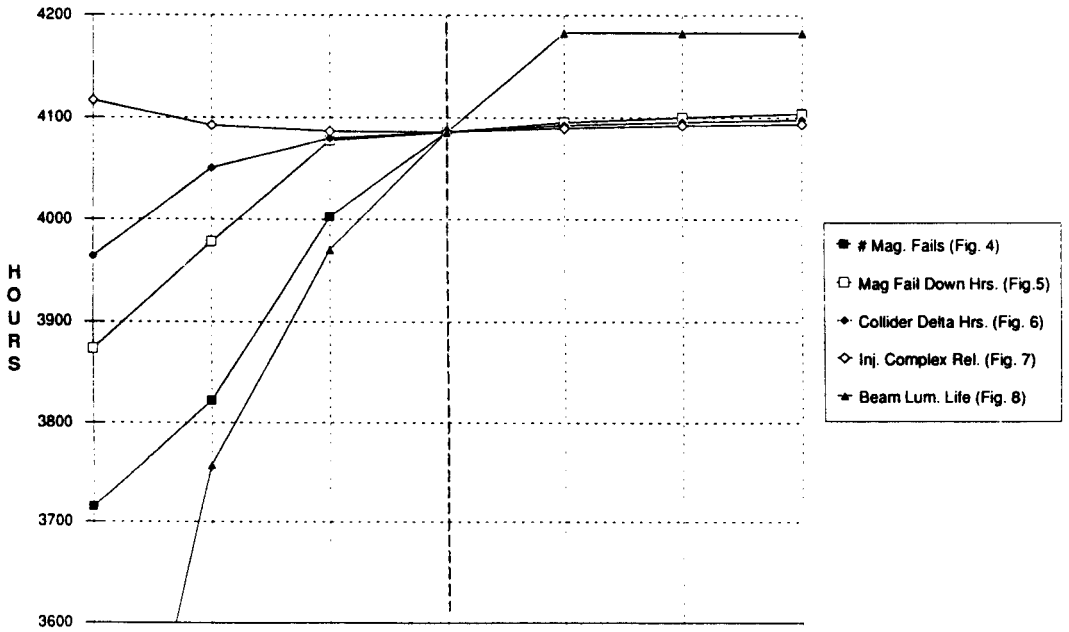

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Figure 9.2. Stable Beam Time Per Year.

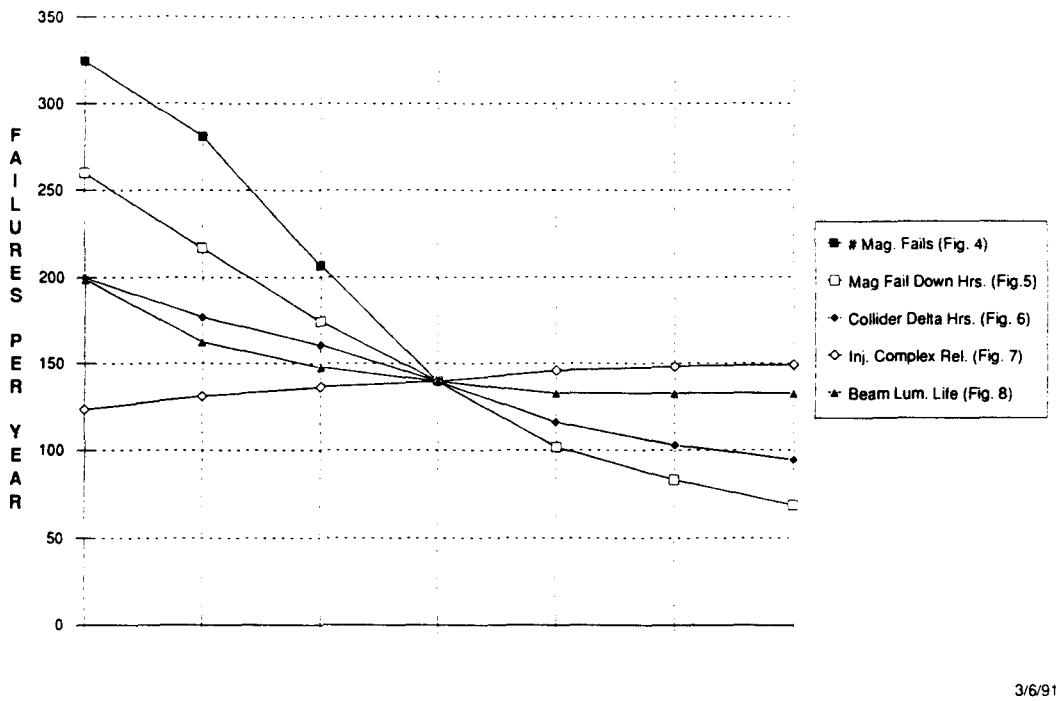

Figure 9.3. Collider Failure Count Sensitivity.

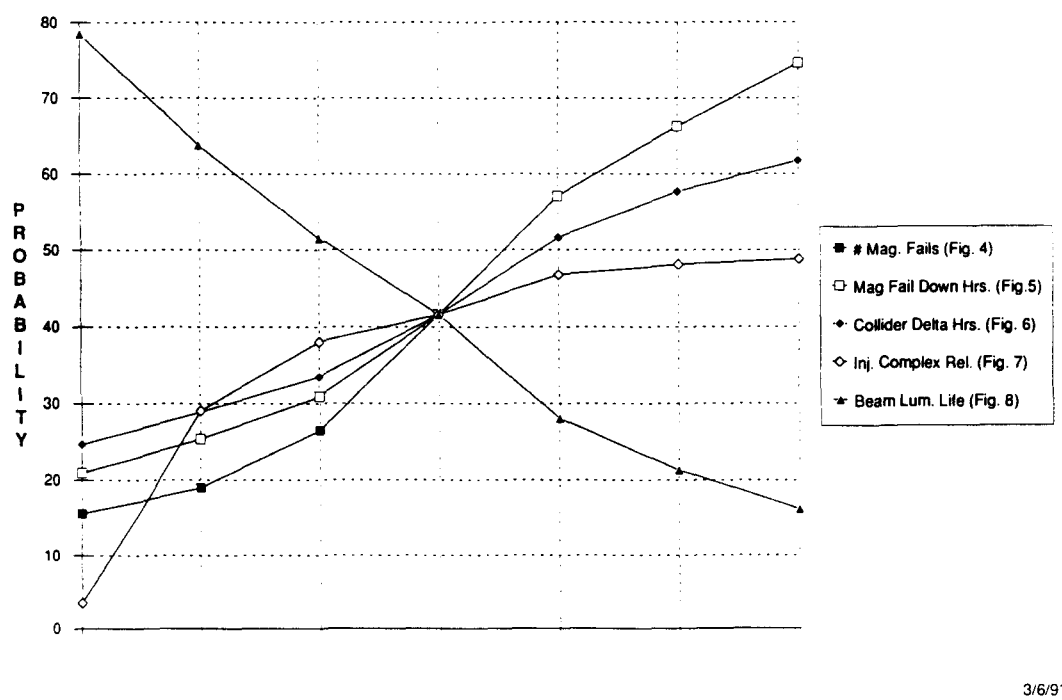

Figure 9.4. Collider/Gas Cycle Reliability Sensitivity.

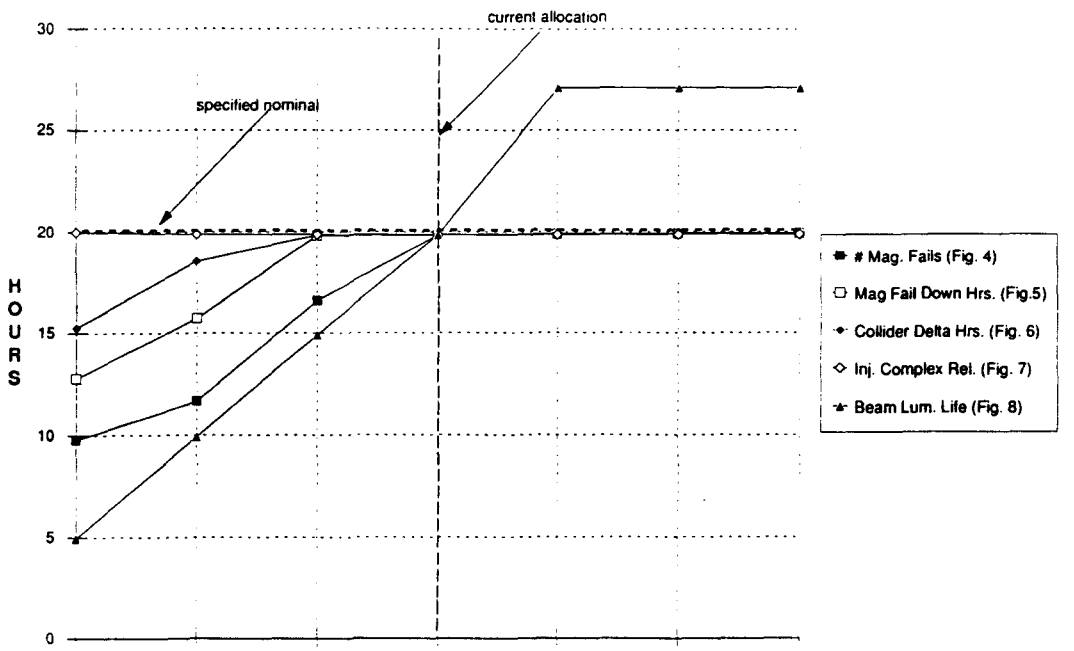

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Figure 9.5. Stable Beam Time Per Cycle Reliability.

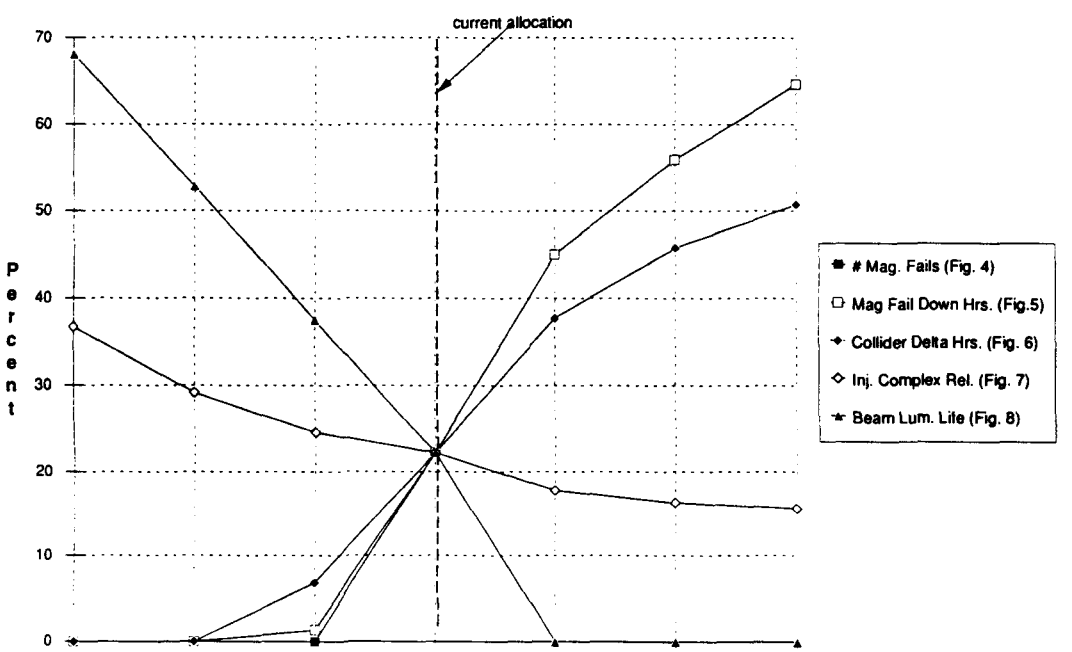

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Figure 9.6. Complete Cycle/Total Cycle Count Sensitivity.

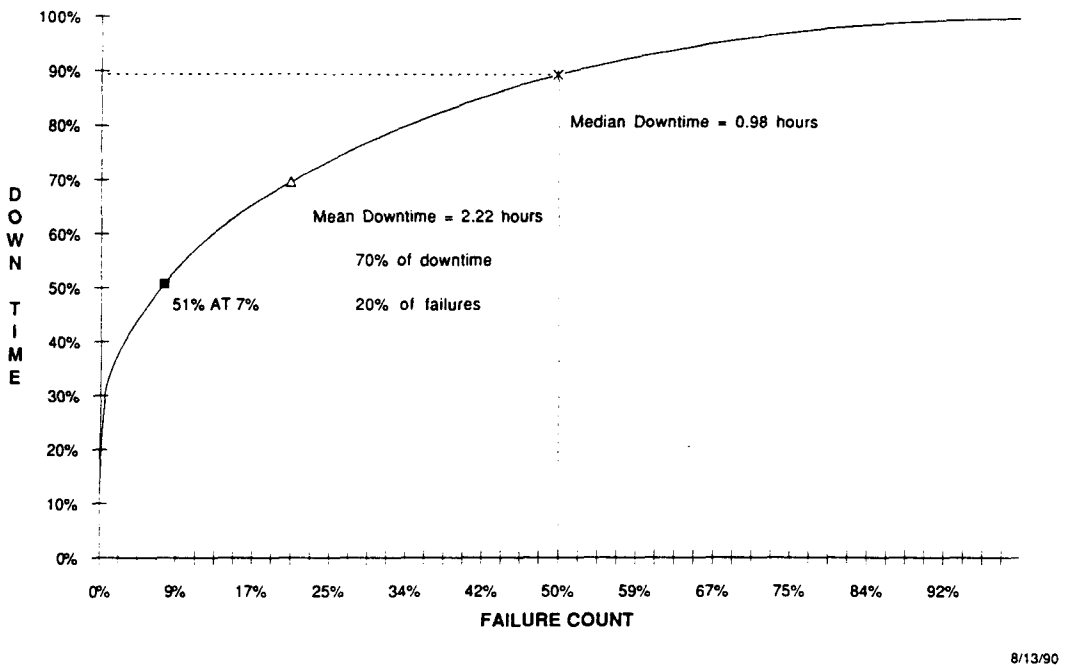

Figure 10. Tevatron Downtime Pareto Analysis.

CONCLUSIONS AND RECOMMENDATIONS

Figure 11 shows the allocated values at the SSC Accelerator segment specification level. Figure 12 shows the allocation down to the major component level for the Collider Accelerator and Collider Magnet Systems elements. Table 4 shows the magnet level reliability allocations compatible with the Collider Magnet System and HEB Magnet System availability allocation. Allocation of the other segment values to lower levels is in progress.

Comparison of the allocated number of failures with the number of failures occurring for similar subsystems at FNAL show that significant reliability improvements must be made in all subsystems outside the Injector Complex. Not only are the required failure counts smaller, the hardware complexity is greater, and the hardware in many cases is spread around a 54-mile tunnel instead of a 3.9-mile tunnel, making fault isolation and repair time potentially hours longer.

Subsystem and magnet-level reliability requirements allocated from the SSC Accelerator availability requirement will not be achieved without significant, systematic attention to the design details that ultimately drive the reliability achievement. A significant part of the availability achievement program will be the expansion, detailed development, and maintenance of the model initiated with this analysis. Proper model development and maintenance will promote availability growth tracking and visibility of the design features most likely to prevent availability achievement. Ranking of problem areas will guide incorporation of the most effective change actions, leading to availability achievement at minimum cost.

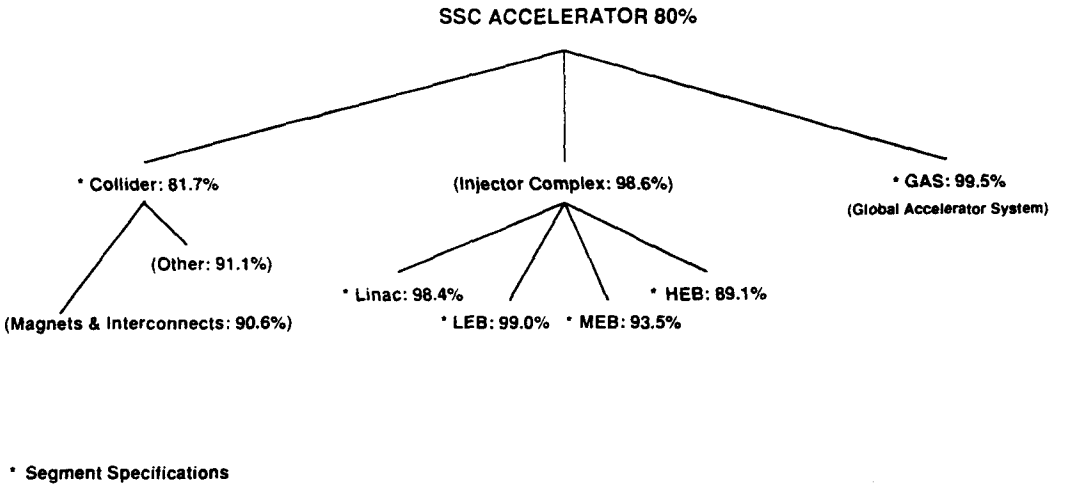

Figure 11. SSC Accelerator Availability Allocation.

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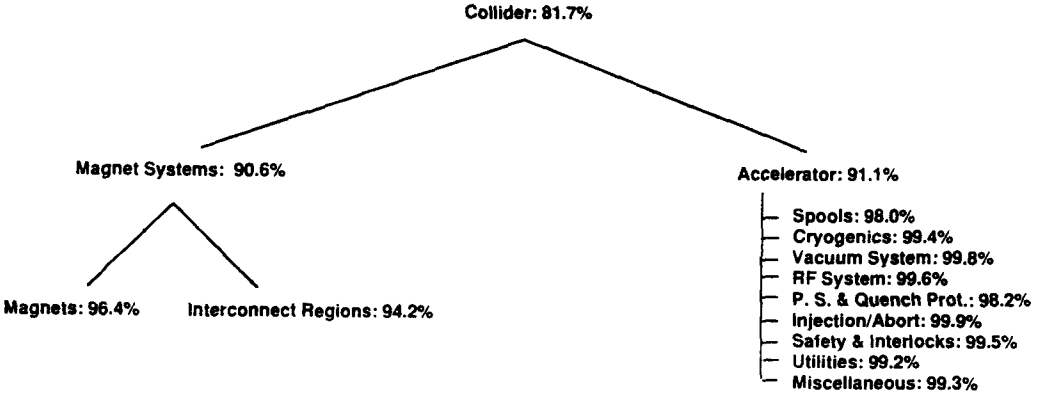

Figure 12. SSC Accelerator Availability Allocation.

Table 4. Collider Magnet System Reliability Allocation.

	# Types	QTY	UNIT AVAIL.	Unit MTBF (Years)	Unit F. R. (Failures/ Billion Hrs.)	25 Year # Unit Failures	25 Year # Failures Incl. I.R.	Annual # Failures Incl. I.R.	F. R. (Failures/ Billion Hrs.) Incl. I.R.	ANNUAL AVAIL.
Dipoles		8596								
CDM	2	8460	0.9999956	6,501	17.56	32.53	79.44	3.18	**42.88**	0.9730
Vertical, BV1	2	64	0.9999911	3,250	35.12	0.49	0.85	0.03	**60.44**	0.9996
Vertical, BV2	2	72	0.9999823	1,625	70.24	1.11	1.51	0.06	**95.56**	0.9991
Quadrupoles		1960								
CQM	1	1664	0.9999956	6,501	17.56	6.40	15.62	0.62	**42.88**	0.9947
Dispersion suppressor, QS	4	120	0.9999911	3,250	35.12	0.92	1.59	0.06	**60.44**	0.9992
M-1, QV	1	64	0.9999823	1,625	70.24	0.98	1.34	0.05	**95.56**	0.9992
Low beta focusing, QL	6	40	0.9999911	3,250	35.12	0.31	0.53	0.02	**60.44**	0.9997
Medium beta focusing, QM	6	40	0.9999911	3,250	35.12	0.31	0.53	0.02	**60.44**	0.9997
Utility region, QU	4	32	0.9999911	3,250	35.12	0.25	0.42	0.02	**60.44**	0.9998
COLLIDER MAGNET TOTAL		10556	0.9501731	0.58	18.73	43.30	101.82	4.07	44.05	0.9641
INTERCONNECT REGIONS (IR) *		12568	0.9999936	4,509	25.32	69.68	**69.68**	**2.79**	25.32	0.9423
			0.9198228	0.36						
SPOOLS										
SP	1	900	0.9999867	2,167	52.68	10.38	15.37	0.61	78.00	0.9914
SPR	4	978	0.9999845	1,857	61.46	13.16	18.59	0.74	86.78	0.9891
SPC	3	1309	0.9999991	32,504	3.51	1.01	1.73	0.07	6.04	0.9992
SPC (Empty)(20%)	1	327	0.9999999	325,043	0.35	0.03	0.04	0.00	0.60	0.99998
SPOOL TOTAL		3514	0.9717177	1.02		24.58	35.73	1.43	46.43	0.9796
HEB										
Dipoles		432	0.9999934	4,334	26.34	2.49	4.89	0.20	**51.66**	0.9979
Quads		234	0.9999947	5,417	21.07	1.08	2.38	0.10	**46.39**	0.9991
Special quads		44	0.9999889	2,600	43.90	0.42	0.67	0.03	**69.22**	0.9996
Spools		250	0.9999856	2,000	57.07	3.12	4.51	0.18	82.39	0.9974
Interconnects		960	0.9999936	4,509	25.32	5.32	**5.32**	**0.21**	25.32	0.9956
HEB TOTAL		1920	0.9856836	2.01		12.44	12.44	0.50	29.59	0.9897
COLLIDER TOTAL			0.842	0.18		137.56	137.56	5.50		0.8860
TOTAL (Including HEB)			0.827	0.17		150.00	150.00	**6.00**		0.8757

* Assumes no bellows required for SPC spool IR; empty SPC IR C. F. = 10% of normal IR, other SPC IR C. F. = 50% of normal IR.

KTD 1/30/91

REFERENCES

1. H. Edwards and R. Stefanski, "Availability—Mission Profile—Collider Operations," memorandum, September 21, 1990.