LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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LIGO SUSPENSION SYSTEM RELIABILITY PREDICTION REPORT

LIGO Systems Engineering

This is an internal working note
of the LIGO Project.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

A reliability prediction was performed on the various components of the Suspension Assembly using the RELEX 217 software package. Reliability predictions for electronic components were performed using the failure rate models of MIL-HDBK-217 and the Ground Benign operating environment. MIL-HDBK-217F defines the Ground Benign environment as:

> "Nonmobile, temperature and humidity controlled environments readily accessible to maintenance; includes laboratory instruments and test equipment, medical electronic equipment, business and scientific computer complexes, and missiles and support equipment in ground silos."

The SUS Subassembly is comprised of the Structural Frame, the Suspension Components, the Magnet/Standoff Assemblies and the Sensor/Actuator Head Assemblies. Based upon the temperature information presented in T960148-01, an ambient temperature of 40^{o}C was used to calculate the failure rate of electronic components within the vacuum environment. Based upon industry standards, a value of 0.001 FPMH was used for structural and mechanical components. The predicted failure rate for the SUS Subassembly, λ_{sub}, is 1.1821 FPMH. The RELEX 217 report, detailing the SUS Subassembly reliability predictions, is provided in Appendix A.

Detailed design information was not available for the SUS Control Electronics of the full scale LIGO. Therefore, failure rate predictions were performed on the SUS Preamplifier and SUS Controller of the 40M Model in order to establish a reliability baseline for the SUS Control Electronics of the full scale LIGO. The SUS Control Electronics is outside the vacuum environment. Therefore, the electronic component ambient temperature was calculated using a 25^{o}C ambient room temperature plus a 10^{o}C temperature rise due to the heat dissipation from surrounding electronic modules. As a result, an ambient temperature of 35^{o}C was used to calculate the failure rate for the electronic components of the SUS Control Electronics.

The predicted failure rate for the SUS Preamplifier, λ_{amp}, is 9.2409 FPMH. The predicted failure rate for the SUS Controller, λ_{cntl}, is 39.0701 FPMH. The RELEX 217 reports, detailing the SUS Preamplifier and the SUS Controller reliability predictions, are provided in Appendices B and C, respectively.

The predicted failure rate for each Suspension Assembly, λ_{SA}, is:

$$\lambda_{SA} = \lambda_{sub} + \lambda_{amp} + \lambda_{cntl} = 1.1821 + 9.2409 + 39.0701 = 49.4931 \text{ FPMH}.$$

The Suspension Assembly MTBF is 20,205 hours.

Availability predictions were performed by developing fault trees using the FaultTree+ software. A fault tree was developed and an Availability prediction was performed on the HIF1 SUS and the HIF2 SUS. The following assumptions were made in performing the Availability predictions:

- LOS1 = LOS2 = SOS
- The predicted MTBF for each Suspension Assembly = 20,205 hours

- The design margins on the structural components minimizes the failure rate. As a result, the probability of failure for each of the structural components is also low resulting in a minimal contribution to the overall availability calculation. Therefore, structural components were omitted from the fault tree for simplification purposes.
- The MDT associated with repair actions for SUS components located within the vacuum environment was assumed to be 72 hours.
- The MDT associated with repair actions for SUS Control Electronics located outside the vacuum environment was assumed to be 6 hours.

With the predicted MTBF for each Suspension Assembly equalling 20,205 hours, an adjustment to the MDT became necessary. The MDT adjustment was necessary in order to achieve the SUS allocated annual Availability in the LIGO 3X operating mode. Since the SUS Control Electronics will be located outside the vacuum environment and will not require a bake-out following a repair action, the MDT estimate was reduced to 6.0 hours. This remains a conservative estimate in that 6.0 hours is the maximum MDT which will still allow achievement of the SUS allocated annual Availability in the LIGO 3X operating mode.

The fault tree for the HIF1 SUS is provided in Appendix D. The calculations indicate that the HIF1 SUS Availability is 0.9960. Since the number of Suspension Assemblies is the same for the HIF1 SUS and the LIF1 SUS, A_{HIF1}=A_{LIF1}=0.9960.

The fault tree for the HIF2 SUS is provided in Appendix E. The calculations indicate that the HIF2 SUS Availability is 0.9951.

Availability predictions were then performed for the three LIGO operating modes. Fault trees for the three LIGO operating modes were developed using the results of the HIF1 and HIF2 SUS availability predictions. The fault trees and Availability predictions for the three LIGO operating modes are provided in Appendices F through H. The results of the SUS availability predictions for each of the LIGO operating modes are summarized below.

Mode of Operation	*Allocated Annual Availability*	*Predicted Annual Availability*
3X	0.9839	0.9871
2X	0.9946	0.9959
1X	1.0000	1.0000

Based upon the available design information, the SUS Availability predictions indicate that the SUS will meet, or exceed, the Availability necessary to achieve the top level LIGO Availability requirements.

1.0 INTRODUCTION

Various suspension components are integrated with the Core Optics Component (COC) in the interferometer and into the Input/Output Optic (IOO) systems. For purposes of this report, the COC and the IOO suspension components, in addition to the suspension components for the other suspended components, are combined into what is defined as the Suspension (SUS) System.

Reliability, repair time and availability calculations were performed on the SUS System of the Laser Interferometer Gravitational Wave Observatory (LIGO). Failure rate data was obtained from the following sources:

- “Non-Electronic Parts Reliability Data 1995,” NPRD-95, Reliability Analysis Center.
- “Reliability Prediction Of Electronic Equipment,” MIL-HDBK-217F, December 1991.
- Engineering estimates predicated upon experience with equipments of similar complexity.

The calculations were predicated upon the design information available at the time this report was prepared. This report will be updated to reflect the current design if the differences in design or material/part selection are likely to significantly impact reliability or availability.

2.0 ACRONYMS

A	Operational Availability
ASSY	Assembly
BS	Beam Splitter
ETM	End Test Mass
FI	Faraday Isolator
FM	Fold Mirror
FPMH	Failures Per Million Hours
FTA	Fault Tree Analysis
HIF1	Interferometer, 4 km long, at Hanford, Washington site
HIF2	Interferometer, 2 km long, at Hanford, Washington site
ITM	Input Test Mass
LED	Light Emitting Diode
LIF1	Interferometer, 4 km long, at Livingston, Louisiana site
LBSC	Beam Splitter Chamber at Livingston, Louisiana site
LHAM	Horizontal Access Module at Livingston, Louisiana site
LIGO	Laser Interferometer Gravitational Wave Observatory
LOS1	Large Optics Suspension 1 Subsystem
LOS2	Large Optics Suspension 2 Subsystem
MC	Mode Cleaner
MDT	Mean Down Time
MMT	Mode Matching Telescope
MTBF	Mean Time Between Failure (λ^{-1})
N/A	Not Applicable
Q	Operational Unavailability
RM	Recycling Mirror
SA	Suspension Assembly
SOS	Small Optics Suspension Subsystem
SUS	Suspension System
WBSC	Beam Splitter Chamber at Hanford, Washington site
WHAM	Horizontal Access Module at Hanford, Washington site
λ	Failure Rate

3.0 APPLICABLE DOCUMENTS

The documents containing Suspension System (SUS) design requirements, SUS design, LIGO reliability requirements and guidelines, reliability modeling and prediction methods, and the software used to perform the reliability predictions and availability calculations are listed in the tables below.

Table 1: Project Documents

LIGO-E960099-B-E	LIGO Reliability Program Plan
LIGO-T950011-17-D	Suspension Design Requirements
LIGO-T960074-07-D	Suspension Preliminary Design
LIGO - E950018-02-E	LIGO Science Requirements Document
D961287-00-C	40 Meter BS and RCM Suspension System Diagram
D961288-00-C	BS and RCM Suspension Controller
D961289-00-C	BS & RCM Suspension Satellite Amplifier
D960011-00-C	SENSOR/ACTUATOR HEAD ASSEMBLY
T960148-01-D	Maximum Current of the Suspension Actuator Coil

Table 2: Reliability Standards and Handbooks

MIL-STD-785	Reliability Program for Systems and Equipment Development and Prediction
MIL-STD-756	Reliability Modeling and Prediction
MIL-HDBK-217F	Reliability Prediction For Electronic Equipment
NRPD-95	Non-Electronic Parts Reliability Data 1995, Reliability Analysis Center

Table 3: Reliability Software

RELEX 217	Reliability prediction software; hardware failure rate calculations.
ITEM Software FaultTree+	Fault tree analysis software; Availability calculations

4.0 RELIABILITY REQUIREMENTS

The LIGO top level system availability requirements are summarized in Table 4 below:

Table 4: LIGO System Reliability Requirements

Mode of Operation	*Annual Availability*	*Minimum Continuous Operating Period*
1X	0.90%	40 hours
2X	0.85%	100 hours
3X	0.75%	100 hours

The Modes of Operation are defined as:

a. Single Operations Mode (1X): At least one of the three interferometers is operational.

b. Double Operations Mode (2X): At least two interferometers are operational. One of which must be the Louisiana interferometer.

c. Triple Operations Mode (3X): All three interferometers are operational.

As described in the LIGO Reliability Program Plan, the allocated subsystem availability requirements were derived from the observatory availability requirements for the 3X mode of operation. With respect to availability, the 3X mode of operation represents the worst case operating scenario. For the reader's convenience, the subsystem availability requirements are presented in Table 5. The SUS availability requirements are highlighted. In the process of allocating the subsystem availability requirements, it was assumed that the 4 km and the 2 km interferometers were of equal complexity. Therefore, since there are two interferometers at the Washington Observatory, the subsystems at the Washington Observatory were assumed to be twice as complex as the respective subsystems at the Louisiana Observatory. As a result, the Washington Observatory subsystem Mean-Time-Between-Mission-Critical-Failure (MTBMCF) values are half of the respective subsystem MTBMCF values at the Louisiana Observatory. The Beam Tube, Facilities Monitoring and Control System, Heating, Ventilation and Air Conditioning, and Electrical Power are exceptions to this rule. These four subsystems were considered to be of equal complexity at each observatory.

MTBMCF is the mean time between subsystem failures which would jeopardize the collection and validation of science data. The MTBMCF takes into consideration equipment redundancies which might be present within the subsystem.

Table 5: Subsystem Availability Allocations

SUBSYSTEM	*OBSERVATORY*					
	LOUISIANA			*WASHINGTON*		
	MTBMCF (Op. Hours)	*MDT (Hours)*	*A*	*MTBMCF (Op. Hours)*	*MDT (Hours)*	*A*
CDS C&M	17, 600	24	0.9986	8, 800	24	0.9973
CDS DAQ	17, 600	24	0.9986	8, 800	24	0.9973
CDS Infrastructure	17, 600	24	0.9986	8, 800	24	0.9973
VCMS	17, 600	24	0.9986	8, 800	24	0.9973
ASC	20, 000	72	0.9964	10, 000	72	0.9929
LSC	20, 000	72	0.9964	10, 000	72	0.9929
COC	26, 000	72	0.9972	13, 000	72	0.9945
COS	24, 000	72	0.9970	12, 000	72	0.9940
IOO	10, 000	72	0.9929	5, 000	72	0.9858
PSL	5, 000	72	0.9858	2, 500	72	0.9720
SEI	13, 000	72	0.9945	6, 500	72	0.9890
SUS	**13, 000**	**72**	**0.9945**	**6, 500**	**72**	**0.9890**
PEM	17, 600	24	0.9986	8, 800	24	0.9973
BT	35, 000	1, 460	0.9600	35, 000	1, 460	0.9600
FMCS	17, 600	24	0.9986	17, 600	24	0.9986
HVAC	17, 600	72	0.9959	17, 600	72	0.9959
ELEC. PWR.	8, 800	24	0.9973	8, 800	24	0.9973
VE	8, 800	72	0.9919	4, 400	72	0.9839

Mean-Down-Time (MDT) is the total preventive and corrective maintenance time divided by the total number of preventive and corrective maintenance actions for a given subsystem. Logistic delays are included in the calculation of preventive and corrective maintenance times. The subsystem MDT requirements are based upon subsystem. size, complexity, and the fact that some subsystems may require a bake-out following maintenance actions. The MDT requirement should be used as a guide in the development of on-site spares and maintenance support policies.

Availability is defined as the ability of an item, under the combined aspects of its reliability and maintenance, to perform its required function over a given period of time. Mathematically, Availability is approximated as:

$$A = \frac{MTBMCF}{MTBMCF + MDT}$$

Therefore, since availability allows for trade-offs between reliability (MTBMCF) and maintenance (MDT), the subsystem availability allocations are the design constraints which must be met in order to achieve the desired level of observatory availability.

5.0 RELIABILITY ANALYSES

SUS reliability was assessed by means of:

- Reliability Modeling
- Reliability and Availability Predictions
- Fault Tree Analysis

5.1 RELIABILITY MODELING

The SUS Reliability Block Diagram for the LIGO 3X Operating Mode is shown in Figure 1. The Reliability Block Diagram depicts a series model in which it is necessary for the SUS at each of the three Interferometers, the Washington 4km Interferometer SUS (HIF1 SUS), the Washington 2km Interferometer SUS (HIF2 SUS) and the Louisiana 4km Interferometer SUS (LIF1 SUS), to be operational for successful LIGO 3X operation.

The SUS Reliability Model for the LIGO 2X Operating Mode is shown in Figure 2. The combination series/parallel model illustrates that at least the HIF1 SUS or the HIF2 SUS must be operational along with the LIF1 SUS for successful LIGO 2X operation.

The SUS Reliability Model for the LIGO 1X Operating Mode is shown in Figure 3. This parallel model depicts that only one of the three SUS systems (HIF1 SUS, HIF2 SUS or LIF1 SUS) is required to be operational for successful LIGO 1X operation.

The SUS for each Interferometer consists of three different types of Suspension Assemblies. The size of the suspended optic determines which type of Suspension Assembly is used. There are two types of Large Optics Suspension Assemblies (LOS1, LOS2) and one type of Small Optics Suspension Assemblies (SOS). All three types of Suspension Assemblies are similar with the exception of size.

Figure 1: SUS Reliability Block Diagram For The LIGO 3X Operating Mode

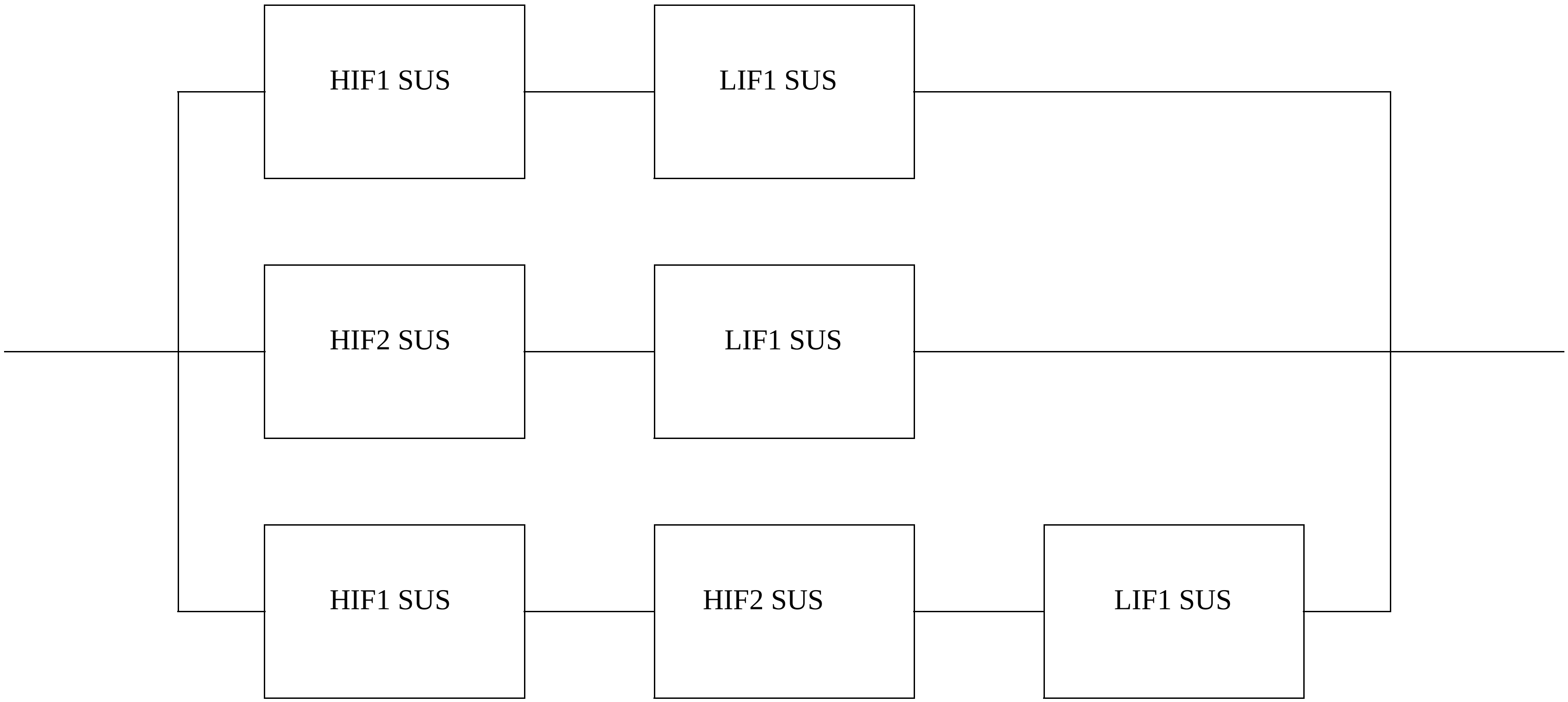


Figure 2: SUS Reliability Block Diagram For The LIGO 2X Operating Mode

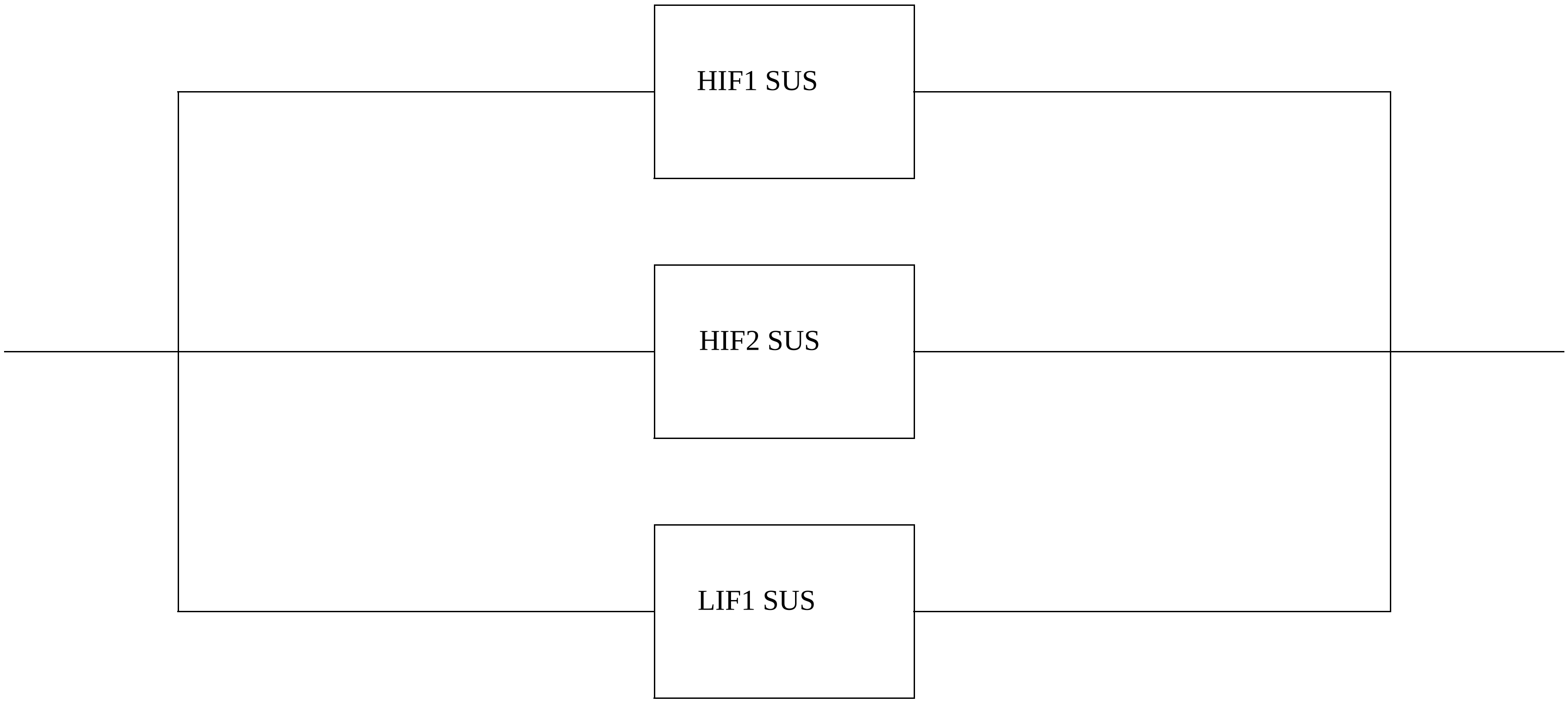


Figure 3: SUS Reliability Block Diagram For The LIGO 1X Operating Mode

The HIF1 SUS and the LIF1 SUS each contain thirteen Suspension Assemblies. The HIF2 SUS contains sixteen Suspension Assemblies. The HIF2 SUS has two additional LOS1 Assemblies and one additional SOS Assembly. The three additional HIF2 Suspension Assemblies are required to suspend three additional Fold Mirrors. Figure 4 shows the Reliability Model for the HIF2 SUS. The model shows that there are eight LOS1 Suspension Assemblies, one LOS2 Suspension Assembly, and seven SOS Suspension Assemblies. Each of the 16 Suspension Assemblies must be operational in order for successful operation of the HIF2 SUS. The Reliability Models for the HIF1 SUS and the LIF1 SUS would be the same as Figure 4 except that there would be six LOS1 Suspension Assemblies, one LOS2 Suspension Assembly, and six SOS Suspension Assemblies. Table 6 identifies the suspended optic, its respective Suspension Assembly, and its location within the Interferometer.

Figure 5 shows the Reliability Block Diagram for an individual Suspension Assembly. The size differences between the LOS1, LOS2 and SOS Suspension Assemblies do not impact the results of the reliability modeling and/or predictions. Therefore, for the purposes of this report, the three different types of Suspension Assemblies are considered equivalent.

The series models indicate that there are not any redundancies present within the Suspension Assemblies or within the Suspension System for each interferometer. Therefore, for the purposes of this report, the MTBMCF is equivalent to the Mean-Time-Between-Failure (MTBF).

5.2 RELIABILITY PREDICTION

A reliability prediction was performed on the various components of the Suspension Assembly using the RELEX 217 software package. Table 7 identifies the failure rate data source for each component of the Suspension Assembly.

Reliability predictions for electronic components were performed using the failure rate models of MIL-HDBK-217 and the Ground Benign operating environment. MIL-HDBK-217F defines the Ground Benign environment as:

> "Nonmobile, temperature and humidity controlled environments readily accessible to maintenance; includes laboratory instruments and test equipment, medical electronic equipment, business and scientific computer complexes, and missiles and support equipment in ground silos."

Reference Figure 5. For purposes of this report, the SUS Subassembly is comprised of the Structural Frame, the Suspension Components, the Magnet/Standoff Assemblies and the Sensor/Actuator Head Assemblies. Based upon the temperature information presented in T960148-01-D, an ambient temperature of 40^oC was used to calculate the failure rate of electronic components within the vacuum environment. Based upon industry standards, a value of 0.001 FPMH was used for structural and mechanical components. The predicted failure rate for the SUS Subassembly, λ_{sub}, is 1.1821 FPMH. The RELEX 217 report, detailing the SUS Subassembly reliability predictions, is provided in Appendix A.

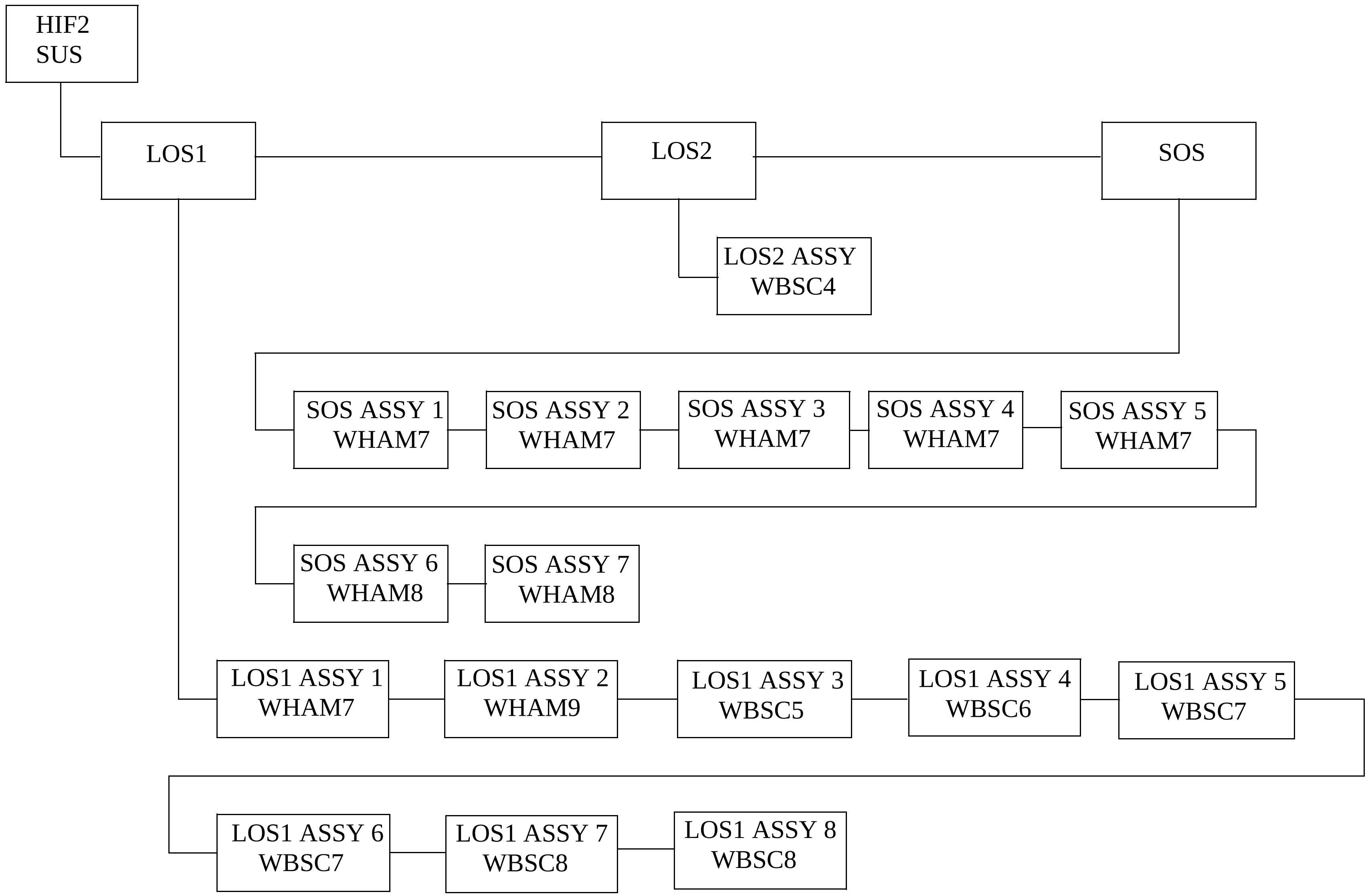


Figure 4: HIF2 Reliability Block Diagram

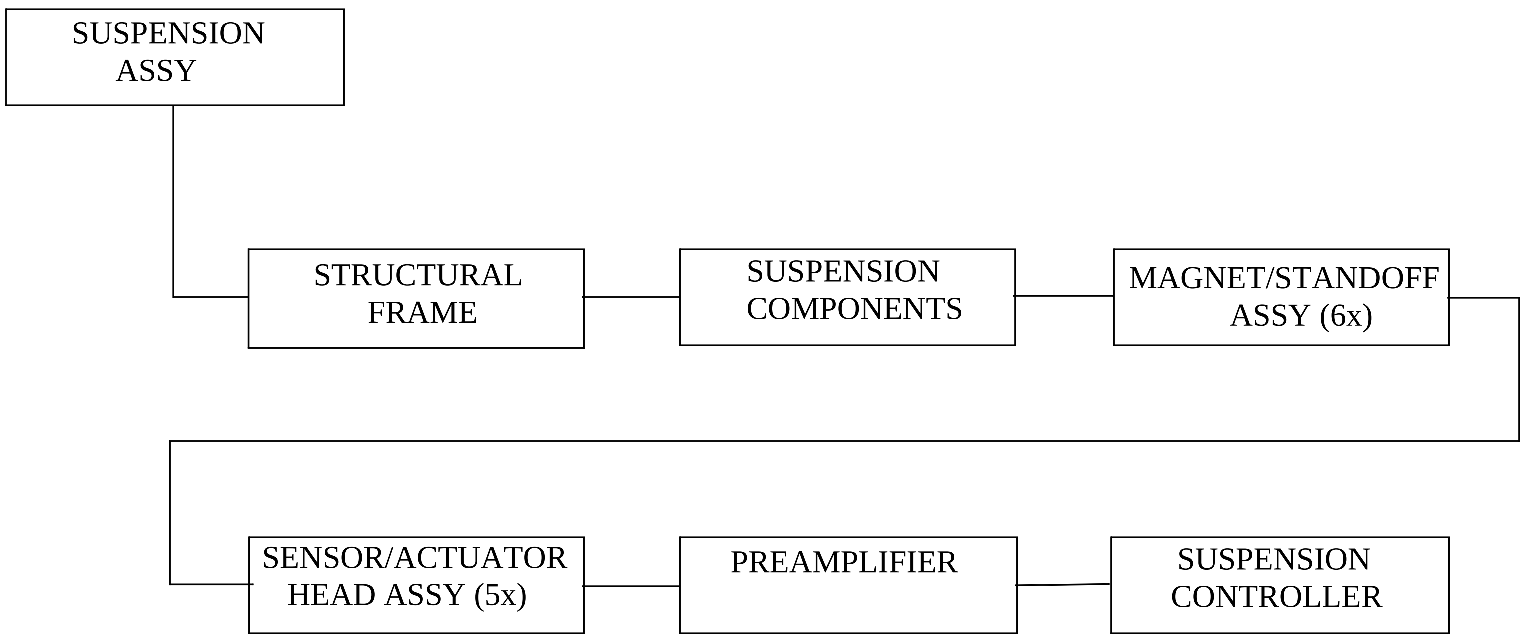


Figure 5: Suspension Assembly Reliability Block Diagram

Table 6: Optics / Suspension Assembly Locations

	SUSPENSION ASSEMBLY			*LOCATION*		
OPTIC	*LOS1*	*LOS2*	*SOS*	*HIF1*	*HIF2*	*LIF1*
ITM_X	X			WBSC3	WBSC7	LBSC3
ITM_Y	X			WBSC1	WBSC8	LBSC1
ETM_X	X			WBSC9	WBSC5	LBSC4
ETM_Y	X			WBSC10	WBSC6	LBSC5
RM	X			WHAM3	WHAM9	LHAM3
BS		X		WBSC2	WBSC4	LBSC2
MMT3	X			WHAM1	WHAM7	LHAM1
MMT2			X	WHAM2	WHAM8	LHAM2
MMT1			X	WHAM1	WHAM7	LHAM1
MC3			X	WHAM1	WHAM8	LHAM1
MC2			X	WHAM1	WHAM7	LHAM2
MC1			X	WHAM1	WHAM7	LHAM1
FM1			X	WHAM1	WHAM7	LHAM1
FM2			X	N/A	WHAM7	N/A
FM_X	X			N/A	WBSC7	N/A
FM_Y	X			N/A	WBSC8	N/A

Table 7: Reliability Data Sources

Description	*Failure Rate (λ) (FPMH)*	*MTBF (Hours)*	*Source*
Preamplifier	9.2409	108,215	MIL-HDBK-217
Controller	39.0701	25,595	MIL-HDBK-217
Height Adapter	0.0010	1×10^9	Engineering Estimate
Stiffening Bars	0.0010	1×10^9	Engineering Estimate
Support Structure	0.0010	1×10^9	Engineering Estimate
Head Holder	0.0010	1×10^9	Engineering Estimate
Wire Standoff	0.0010	1×10^9	Engineering Estimate
Wire Guide Rod	0.0010	1×10^9	Engineering Estimate
Suspension Block	0.0010	1×10^9	Engineering Estimate
Crescent Wire Guide	0.0010	1×10^9	Engineering Estimate
Suspension Wire	0.0010	1×10^9	Engineering Estimate
Magnet	0.0001	10.0×10^9	MIL-HDBK-217
Standoff	0.0010	1×10^9	Engineering Estimate
Coil	0.0001	9.0×10^9	MIL-HDBK-217
LED	0.0029	350.0×10^6	MIL-HDBK-217
Photo Diode	0.0501	20.0×10^6	MIL-HDBK-217
Housing	0.0010	1×10^9	Engineering Estimate
Lead/Lead Wire Connections	0.1300	7.7×10^6	MIL-HDBK-217
Connector, Non-Feed Thru	0.1195	8.4×10^6	MIL-HDBK-217
Connector, Feed Thru	0.1195	8.4×10^6	MIL-HDBK-217

Detailed design information was not available for the SUS Control Electronics of the full scale LIGO. Therefore, failure rate predictions were performed on the SUS Preamplifier and SUS Controller of the 40M Model in order to establish a reliability baseline for the SUS Control Electronics of the full scale LIGO. The SUS Control Electronics is outside the vacuum environment. Therefore, the electronic component ambient temperature was calculated using a 25^oC ambient room temperature plus a 10^oC temperature rise due to the heat dissipation from surrounding electronic modules. As a result, an ambient temperature of 35^oC was used to calculate the failure rate for the electronic components of the SUS Control Electronics.

The predicted failure rate for the SUS Preamplifier, λ_{amp}, is 9.2409 FPMH. The predicted failure rate for the SUS Controller, λ_{cntl}, is 39.0701 FPMH. The RELEX 217 reports, detailing the SUS Preamplifier and the SUS Controller reliability predictions, are provided in Appendices B and C, respectively.

The predicted failure rate for each Suspension Assembly, λ_{SA}, is:

$$\lambda_{SA} = \lambda_{sub} + \lambda_{amp} + \lambda_{cntl} = 1.1821 + 9.2409 + 39.0701 = 49.4931 \text{ FPMH.}$$

The Suspension Assembly MTBF is 20,205 hours.

5.3 AVAILABILITY PREDICTION

Availability predictions were performed by developing fault trees using the FaultTree+ software. A fault tree was developed and an Availability prediction was performed on the HIF1 SUS and the HIF2 SUS. The following assumptions were made in performing the Availability predictions:

- LOS1 = LOS2 = SOS
- The predicted MTBF for each Suspension Assembly = 20,205 hours
- The design margins on the structural components minimizes the failure rate. As a result, the probability of failure for each of the structural components is also low resulting in a minimal contribution to the overall availability calculation. Therefore, structural components were omitted from the fault tree for simplification purposes.
- The MDT associated with repair actions for SUS components located within the vacuum environment was assumed to be 72 hours.
- The MDT associated with repair actions for SUS Control Electronics located outside the vacuum environment was assumed to be 6 hours.

With the predicted MTBF for each Suspension Assembly equalling 20,205 hours, an adjustment to the MDT became necessary. The MDT adjustment was necessary in order to achieve the SUS allocated annual Availability in the LIGO 3X operating mode. Since the SUS Control Electronics will be located outside the vacuum environment and will not require a bake-out following a repair action, the MDT estimate was reduced to 6.0 hours. This remains a conservative estimate in that 6.0 hours is the maximum MDT which will still allow achievement of the SUS allocated annual Availability in the LIGO 3X operating mode.

The fault tree for the HIF1 SUS is provided in Appendix D. The calculations indicate that the HIF1 SUS Availability is 0.9960. Since the number of Suspension Assemblies is the same for the HIF1 SUS and the LIF1 SUS, $A_{HIF1}=A_{LIF1}=0.9960$.

The fault tree for the HIF2 SUS is provided in Appendix E. The calculations indicate that the HIF2 SUS Availability is 0.9951.

Availability predictions were then performed for the three LIGO operating modes. Fault trees for the three LIGO operating modes were developed using the results of the HIF1 and HIF2 SUS availability predictions. The fault trees and Availability predictions for the three LIGO operating modes are provided in Appendices F through H. The results of the SUS availability predictions for each of the LIGO operating modes are summarized in Table 7 below.

Table 8: SUS Availability Predictions For The LIGO Operating Modes

Mode of Operation	*Allocated Annual Availability*	*Predicted Annual Availability*
3X	0.9839	0.9871
2X	0.9946	0.9959
1X	1.0000	1.0000

5.4 40 M MODEL TEST DATA

An evaluation of the 40 M Model test data with regards to the mechanical aspects of the 40 M Suspension Assemblies is presented in this section. At the time of this report, prototype full-scale LIGO SUS control electronic hardware was being installed, debugged and evaluated in the 40 M Model. A reliability assessment at this time would not be valid.

In July 1996, the Test Mass Suspension Assembly was installed into the East Vertex chamber of the 40M Model. The Test Mass Suspension Assembly of the 40M Model is a scaled down version of the LOS Suspension Assembly of the full-scale LIGO. One notable exception, between the two designs, is that the Test Mass Suspension Assembly of the 40M Model is a bolted assembly whereas the LOS Suspension Assembly of the full-scale LIGO is a welded assembly. As of the date of this report, there has only been one failure incident with the Test Mass Suspension Assembly. The failure incident occurred as the result of human error during installation and the occurrence of an earthquake. During installation, the gap between the test mass and the safety stop was set at 2 mm; not 1 mm as specified. As a result, when the earthquake occurred, the extra 1 mm of separation allowed the magnet/standoff assembly to contact the Photodiode and the magnet/standoff assembly separated from the test mass.

In December 1996, the Beam Splitter Suspension Assembly was installed into the 40M Model. The Beam Splitter Suspension Assembly of the 40M Model most closely approximates the SOS Suspension Assembly of the full-scale LIGO. As of the date of this report, there has been no failure occurrences with the Beam Splitter Suspension Assembly.

Since the one failure incident was not the result of a Suspension Assembly hardware failure, but rather the result of human error and an act of God, the failure is considered “non-relevant.” This failure incident would not be charged against the Suspension Assembly in the calculation of a MTBF. However, the failure incident did result in the 40 M Model being inoperative for approximately one week as repairs were made. This results in an Unavailability of approximately 2% from July 1996 - July 1997.

6.0 CONCLUSIONS

The 40 M Test Data does not raise any serious concerns over the Suspension Assemblies achieving the predicted MTBF value. However, the one failure incident which did occur does raise some issues which warrant consideration.

First, procedures, processes and inspections should be reviewed and revised, as necessary, to preclude the reoccurrence of a failure due to human error during installation.

Second, spares policy and repair procedures need to be developed to ensure that the Mean-Down-Time associated with SUS repair actions is limited to 72 hours. This will ensure that the expense associated with storing spares as pre-assembled subassemblies can be avoided.

APPENDIX A: SUS SUBASSEMBLY RELIABILITY PREDICTION

Part Number :
Reference Des:
Date :August 04, 1997
Environment :Ground Benign
Temperature :40.0

Description :Suspension Assy
File Name :SUS2.TRE
Time : 2:31 p.m.
Failure Rate :1.182101
MTBF :845951.624490

Item	Description	Reference Designator	Quantity	Failure Rate	MTBF
Suspension Assy			1	1.182101	845951.624490
SUS1.SUB	Structural Frame	A1	1	0.009000	1.111110e+08
SUS2.SUB	Suspension Components	A2	1	0.007000	1.428570e+08
SUS3.SUB	Magnet/Standoff Assy	A3	6	0.006600	1.515150e+08
SUS4.SUB	Sensor/Actuator Head Assy	A4	5	0.920560	1.086290e+06
SUS5.SUB	Electrical Connections	A5	1	0.238940	4.185150e+06

Part Number :SUS01
Reference Des:A1
Date :August 04, 1997
Environment :Ground Benign
Temperature :40.0

Description :Structural Frame
File Name :SUS1.SUB
Time : 2:31 p.m.
Failure Rate :0.009000
MTBF :1.111110e+08

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	A01	Height Adapter		0.001000	1	0.001000
2	A02	Stiffening Bars		0.001000	4	0.004000
3	A03	Support Structure		0.001000	1	0.001000
4	A04	Head Holder		0.001000	3	0.003000

Part Number :SUS02
Reference Des:A2
Date :August 04, 1997
Environment :Ground Benign
Temperature :40.0

Description :Suspension Components
File Name :SUS2.SUB
Time : 2:31 p.m.
Failure Rate :0.007000
MTBF :1.428570e+08

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	B01	Wire Standoff		0.001000	2	0.002000
2	B02	Wire Guide Rod		0.001000	2	0.002000
3	B03	Suspension Block		0.001000	1	0.001000
4	B04	Crescent Wire Guide		0.001000	1	0.001000
5	B05	Suspension Wire		0.001000	1	0.001000

Part Number :SUS03
Reference Des:A3
Date :August 04, 1997
Environment :Ground Benign
Temperature :40.0

Description :Magnet/Standoff Assy
File Name :SUS3.SUB
Time : 2:31 p.m.
Failure Rate :0.001100
MTBF :9.090910e+08

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	C01	Magnet		0.000100	1	0.000100
2	C02	Standoff		0.001000	1	0.001000

Part Number :SUS04
Reference Des:A4
Date :August 04, 1997
Environment :Ground Benign
Temperature :40.0

Description :Sensor/Actuator Head Assy
File Name :SUS4.SUB
Time : 2:31 p.m.
Failure Rate :0.184112
MTBF :5.431470e+06

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	D01	Coil		0.000111	1	0.000111
2	TLN107A	LED		0.002882	1	0.002882
3	TPS703A	Photo Diode		0.050120	1	0.050120
4	D02	Housing		0.001000	1	0.001000
5	D03	Lead/Lead Wire Connection		0.013000	10	0.130000

Part Number :SUS05
Reference Des:A5
Date :August 04, 1997
Environment :Ground Benign
Temperature :40.0

Description :Electrical Connections
File Name :SUS5.SUB
Time : 2:31 p.m.
Failure Rate :0.238940
MTBF :4.185150e+06

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	E02	Connector, Non Feed Thru		0.119470	1	0.119470
2	E03	Connector, Feed Thru		0.119470	1	0.119470

APPENDIX B:
SUS PREAMPLIFIER
RELIABILITY PREDICTION

Part Number :SUS06
Reference Des:A6
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Preamplifier
File Name :SUS6.SUB
Time : 2:33 p.m.
Failure Rate :9.240857
MTBF :108215.065929

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	F01	I/O Connectors		0.002387	2	0.004775
2	LT1125	Quad Op Amp		0.118287	17	2.010876
3	LM6321	High Speed Buffer		0.299236	11	3.291601
4	RC	Resistors		0.014569	60	0.874162
5	CK	Capacitors, 0.1uF		0.019775	63	1.245850
6	LM78L15	+15 Volt Regulator		0.522106	3	1.566317
7		Connector	J4	0.047746	1	0.047746
8		Connector	J3	0.047746	1	0.047746
9		Connector	J5	0.047746	1	0.047746
10		PCB		0.104040	1	0.104040

APPENDIX C: SUS CONTROLLER RELIABILITY PREDICTION

Part Number :
Reference Des:
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Suspension Controller
File Name :SUS7.TRE
Time : 2:35 p.m.
Failure Rate :39.070102
MTBF :25595.018806

Item	Description	Reference Designator	Quantity	Failure Rate	MTBF
SUS CONTROLLER			1	39.070102	25595.018806
MAIN.SUB	Main Board	A1	1	6.028522	165878.144605
INPUT.SUB	Input SIP	A1A1−A1A3	3	3.868509	258497.550383
POSTIN.SUB	Post In SIP	A1A4 − A1A5	2	5.441164	183784.215950
COILDRV.SUB	Coil Driver SIP	A1A6 − A1A10	5	5.919658	168928.691541
FILTER.SUB	Filter SIP	A1A11 − A1A15	5	12.141887	82359.520263
LSCIN.SUB	LSC SIP	A1A16	1	3.076556	325038.795950
OUTPUT.SUB	Output SIP	A1A17	1	2.593808	385533.596912

Part Number :D961290
Reference Des:A1A6 − A1A10
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Coil Driver SIP
File Name :COILDRV.SUB
Time : 2:35 p.m.
Failure Rate :1.183932
MTBF :844643.457706

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	LT1125	Quad Op Amp		0.118287	1	0.118287
2	LM6321	High Speed Buffer		0.299236	2	0.598473
3	RC	Resistors		0.014569	10	0.145694
4	CK	Capacitors		0.019775	9	0.177979
5		SIP Connector	P1	0.095492	1	0.095492
6		SIP PCB		0.048008	1	0.048008

Part Number :D961291
Reference Des:A1A11 − A1A15
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Filter SIP
File Name :FILTER.SUB
Time : 2:35 p.m.
Failure Rate :2.428377
MTBF :411797.601313

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	LT1125	Quad Op Amp		0.118287	2	0.236574
2	RC	Resistors		0.014569	24	0.349665
3	CK	Capacitors, 0.1uF		0.019775	18	0.355957
4		SIP Connector	P1	0.095492	1	0.095492
5		SIP PCB		0.018462	1	0.018462
6	LM6321	High Speed Buffer		0.299236	4	1.196946
7	MAX333	Quad SPDT Switch		0.084360	1	0.084360
8	CK	Capacitors, 0.47uF		0.022731	4	0.090923

Part Number :D961293
Reference Des:A1A1-A1A3
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Input SIP
File Name :INPUT.SUB
Time : 2:35 p.m.
Failure Rate :1.289503
MTBF :775492.651149

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	LT1125	Quad Op Amp		0.118287	1	0.118287
2	RC	Resistors		0.014569	16	0.233110
3	CK	Capacitors, 0.1uF		0.019775	4	0.079102
4		SIP Connector	P1	0.095492	1	0.095492
5		SIP PCB		0.058480	1	0.058480
6	1N4148-1	Diode, General Purpose		0.011378	8	0.091021
7	MAX509	Quad Serial 8-Bit DAC		0.614012	1	0.614012

Part Number :D961295
Reference Des:A1A16
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :LSC SIP
File Name :LSCIN.SUB
Time : 2:35 p.m.
Failure Rate :3.076556
MTBF :325038.795950

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	LT1125	Quad Op Amp		0.118287	2	0.236574
2	RC	Resistors		0.014569	19	0.276818
3	CK	Capacitors, 0.1uF		0.019775	20	0.395508
4		SIP Connector	P1	0.095492	1	0.095492
5		SIP PCB		0.024956	1	0.024956
6	1N4148-1	Diode, General Purpose		0.011378	8	0.091021
7	MAX509	Quad Serial 8-Bit DAC		0.614012	1	0.614012
8	DG191A	Dual JFET SPDT Switch		0.072615	2	0.145230
9	LM6321	High Speed Buffer		0.299236	4	1.196946

Part Number :D961288
Reference Des:A1
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Main Board
File Name :MAIN.SUB
Time : 2:35 p.m.
Failure Rate :6.028522
MTBF :165878.144605

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	LT1125	Quad Op Amp		0.118287	8	0.946295
2	RC	Resistors		0.014569	67	0.976147
3	CK	Capacitors, 0.1uF		0.019775	37	0.731690
4		SIP Connector	P1	0.095492	1	0.095492
5		SIP PCB		0.018904	1	0.018904
6	MAX532	Dual Serial 12-Bit DAC		0.888347	1	0.888347
7	DG211	Quad SPST Switch		0.084360	5	0.421798
8	LM78L15	+15 Volt Regulator		0.522106	2	1.044212
9	CK	Capacitors, 1.0uF		0.024329	24	0.583897
10	CK	Capacitors, 5.6uF		0.028409	6	0.170456
11	CK	Capacitors, 22uF		0.032132	4	0.128530
12	1N4148-1	Diode, General Purpose		0.011378	2	0.022755

Part Number :D961292
Reference Des:A1A17
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Output SIP
File Name :OUTPUT.SUB
Time : 2:35 p.m.
Failure Rate :2.593808
MTBF :385533.596912

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	LT1125	Quad Op Amp		0.118287	1	0.118287
2	RC	Resistors		0.014569	16	0.233110
3	CK	Capacitors, 0.1uF		0.019775	6	0.118652
4		SIP Connector	P1	0.095492	1	0.095492
5		SIP PCB		0.072454	1	0.072454
6	1N4148-1	Diode, General Purpose		0.011378	10	0.113776
7	MAX509	Quad Serial 8-Bit DAC		0.614012	3	1.842037

Part Number :D961294
Reference Des:A1A4 - A1A5
Date :August 04, 1997
Environment :Ground Benign
Temperature :35.0

Description :Post In SIP
File Name :POSTIN.SUB
Time : 2:35 p.m.
Failure Rate :2.720582
MTBF :367568.431900

Record Number	Part Number	Description	Reference Designator	Failure Rate, Unit	Qty	Failure Rate, Total
1	LT1125	Quad Op Amp		0.118287	3	0.354860
2	RC	Resistors		0.014569	37	0.539066
3	CK	Capacitors, 0.1uF		0.019775	18	0.355957
4		SIP Connector	P1	0.095492	1	0.095492
5		SIP PCB		0.018904	1	0.018904
6	MAX532	Dual Serial 12-Bit DAC		0.888347	1	0.888347
7	DG211	Quad SPST Switch		0.084360	1	0.084360
8	LM6321	High Speed Buffer		0.299236	1	0.299236
9	MAX333	Quad SPDT Switch		0.084360	1	0.084360

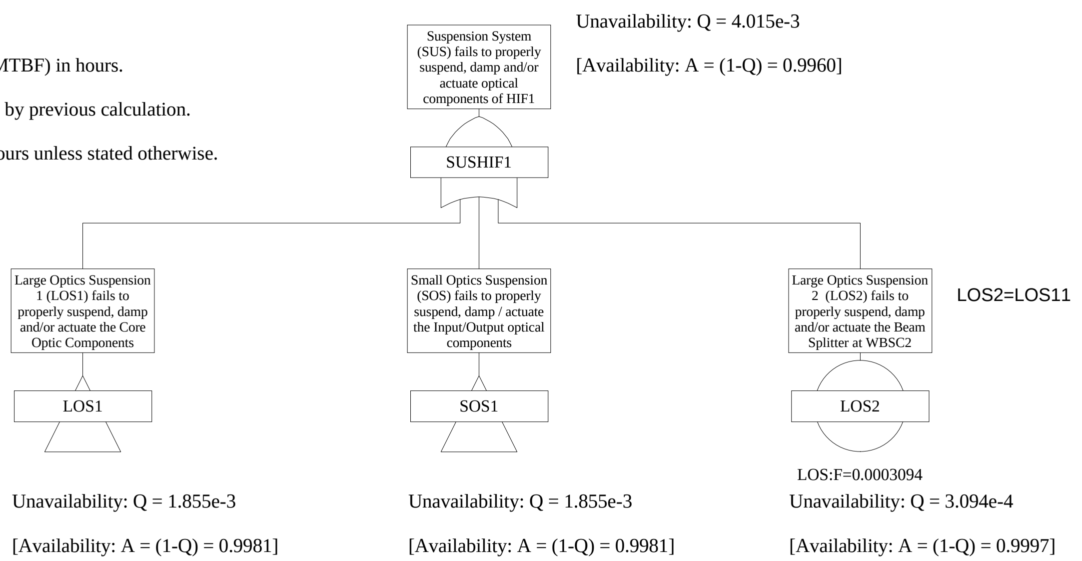
APPENDIX D: HIF1 SUS AVAILABILITY PREDICTION

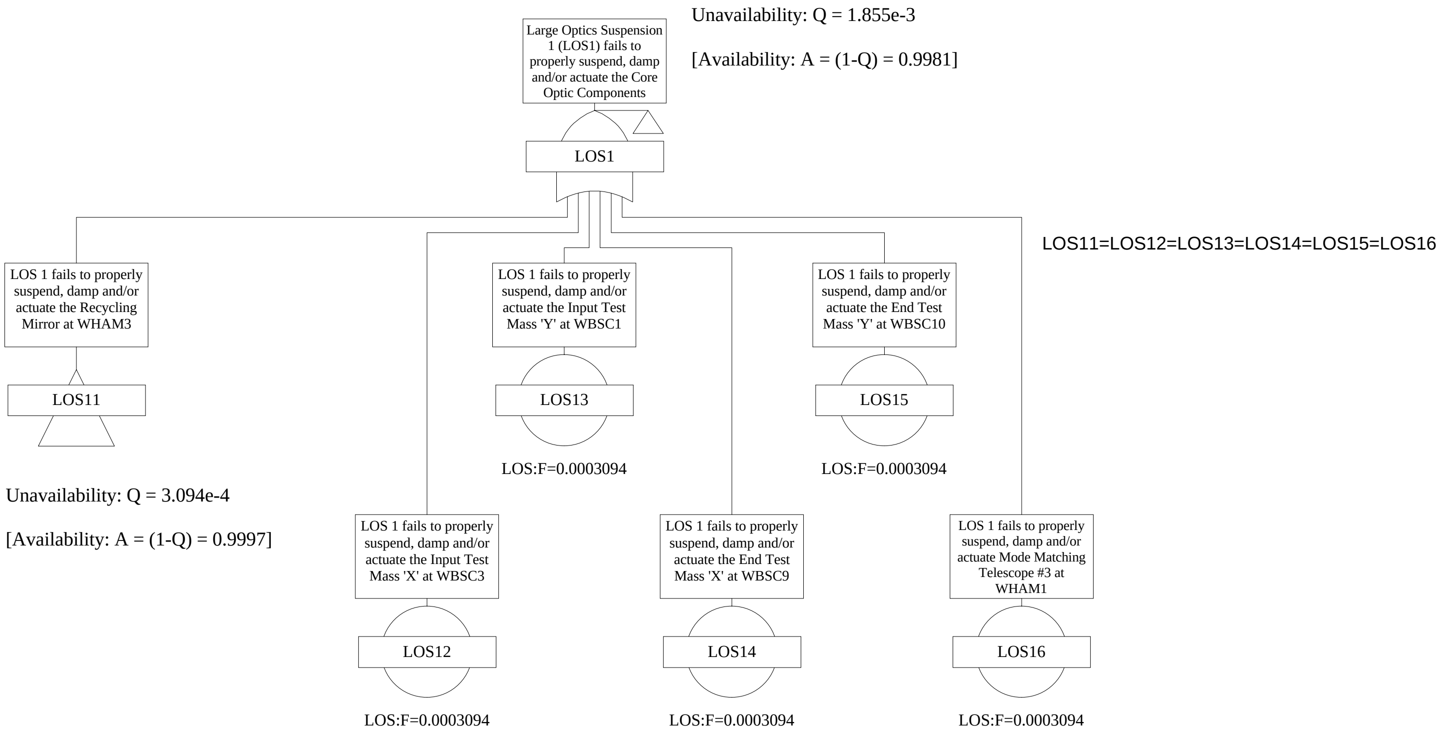
NOTES:

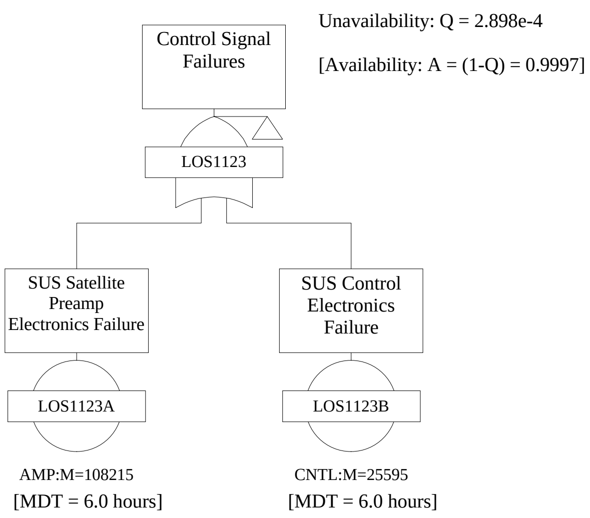
1. M = Mean-Time-Between-Failure (MTBF) in hours.

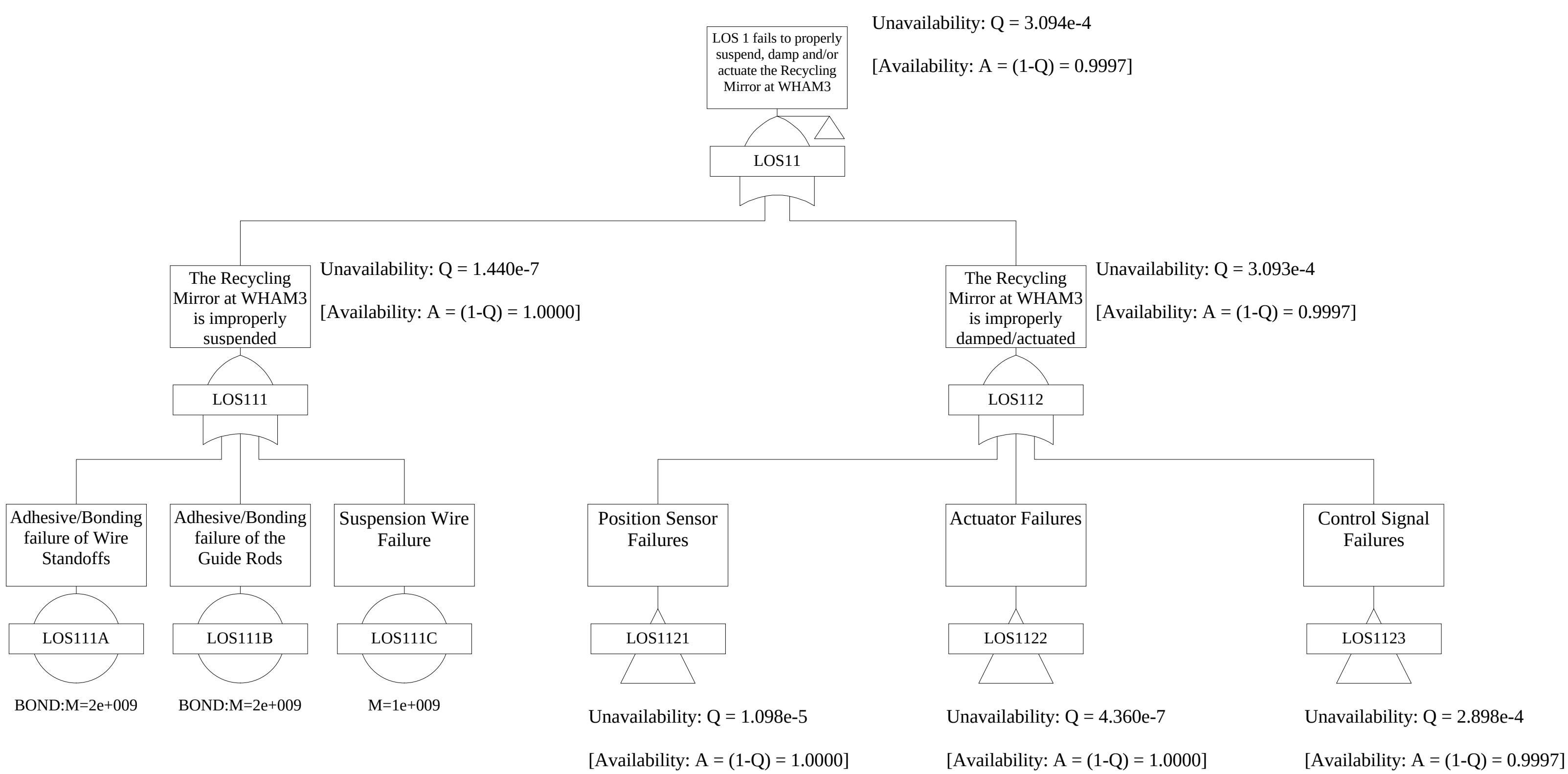
2. F = Fixed Unavailability determined by previous calculation.

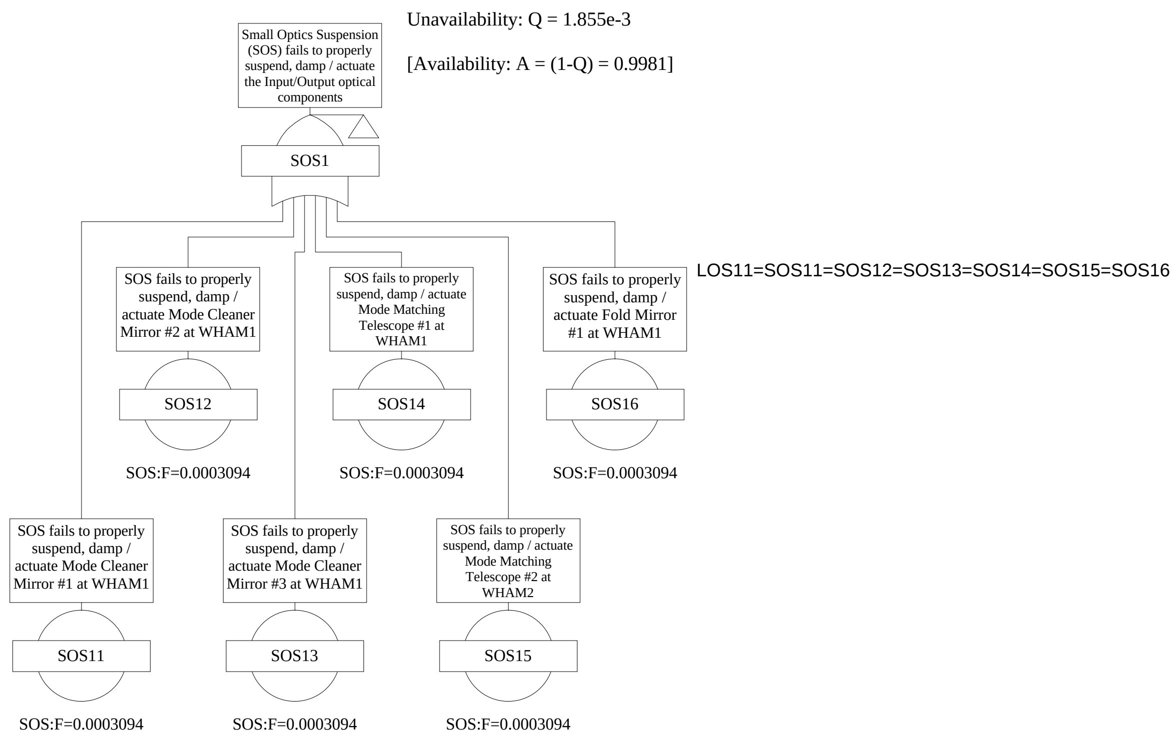
3. MDT = Mean-Down-Time = 72.0 hours unless stated otherwise.

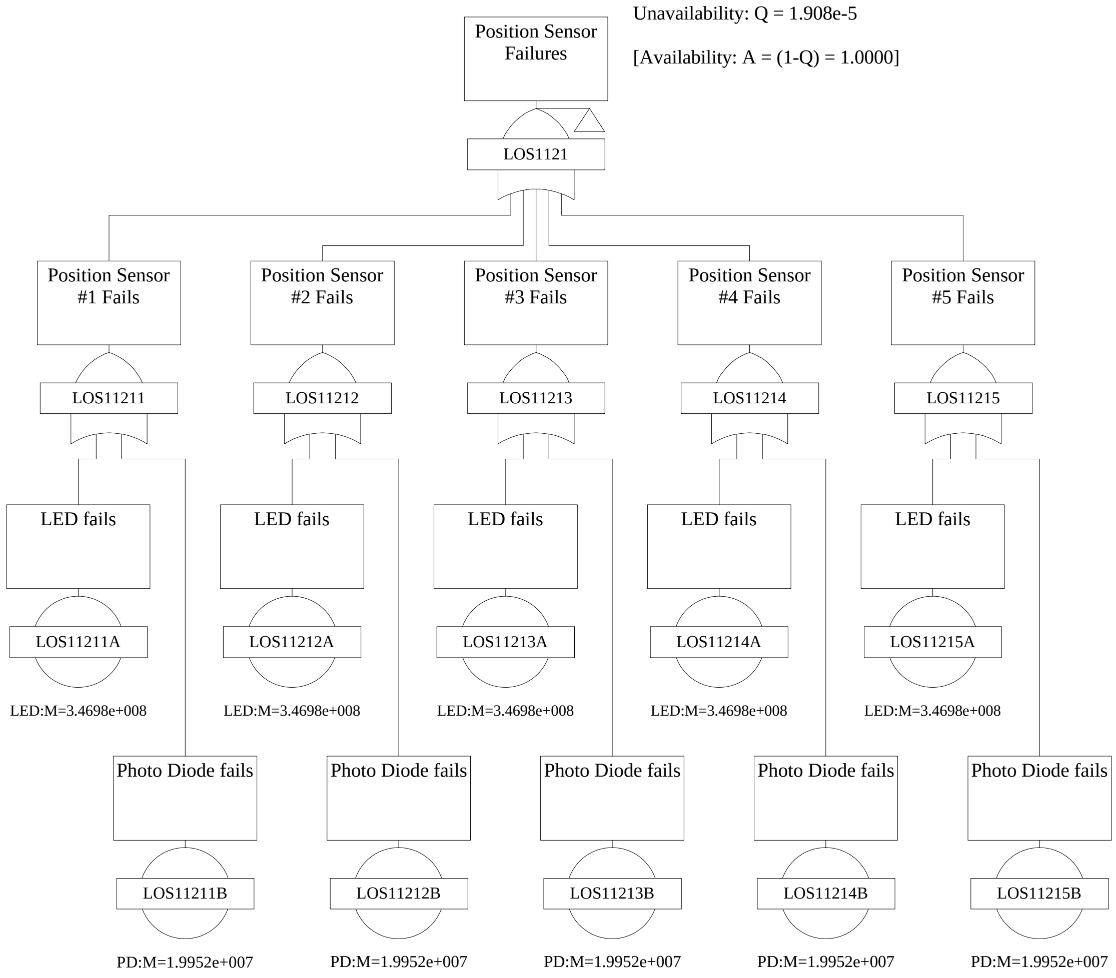


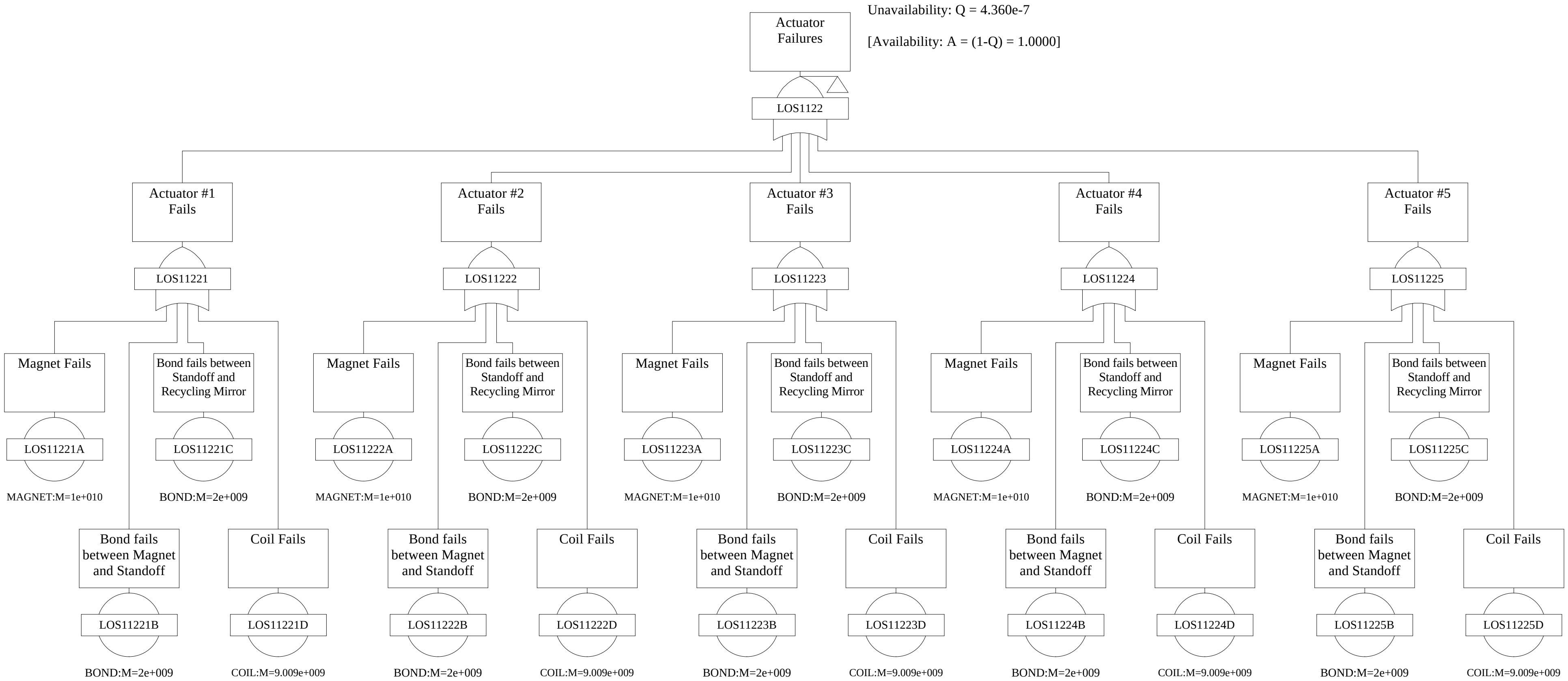

Large Optics Suspension 1 (LOS1) fails to properly suspend, damp and/or actuate the Core Optic Components
Unavailability: Q = 1.855e-3
[Availability: A = (1-Q) = 0.9981]
LOS1
LOS11=LOS12=LOS13=LOS14=LOS15=LOS16
LOS 1 fails to properly suspend, damp and/or actuate the Recycling Mirror at WHAM3
LOS11
Unavailability: Q = 3.094e-4
[Availability: A = (1-Q) = 0.9997]
LOS 1 fails to properly suspend, damp and/or actuate the Input Test Mass 'Y' at WBSC1
LOS13
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate the End Test Mass 'Y' at WBSC10
LOS15
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate the Input Test Mass 'X' at WBSC3
LOS12
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate the End Test Mass 'X' at WBSC9
LOS14
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate Mode Matching Telescope #3 at WHAM1
LOS16
LOS:F=0.0003094


Control Signal Failures
Unavailability: Q = 2.898e-4
[Availability: A = (1-Q) = 0.9997]
LOS1123
SUS Satellite Preamp Electronics Failure
SUS Control Electronics Failure
LOS1123A
LOS1123B
AMP:M=108215
[MDT = 6.0 hours]
CNTL:M=25595
[MDT = 6.0 hours]


LOS 1 fails to properly suspend, damp and/or actuate the Recycling Mirror at WHAM3
Unavailability: Q = 3.094e-4
[Availability: A = (1-Q) = 0.9997]
LOS11
The Recycling Mirror at WHAM3 is improperly suspended
Unavailability: Q = 1.440e-7
[Availability: A = (1-Q) = 1.0000]
LOS111
The Recycling Mirror at WHAM3 is improperly damped/actuated
Unavailability: Q = 3.093e-4
[Availability: A = (1-Q) = 0.9997]
LOS112
Adhesive/Bonding failure of Wire Standoffs
LOS111A
BOND:M=2e+009
Adhesive/Bonding failure of the Guide Rods
LOS111B
BOND:M=2e+009
Suspension Wire Failure
LOS111C
M=1e+009
Position Sensor Failures
LOS1121
Unavailability: Q = 1.098e-5
[Availability: A = (1-Q) = 1.0000]
Actuator Failures
LOS1122
Unavailability: Q = 4.360e-7
[Availability: A = (1-Q) = 1.0000]
Control Signal Failures
LOS1123
Unavailability: Q = 2.898e-4
[Availability: A = (1-Q) = 0.9997]


Unavailability: Q = 1.855e-3
[Availability: A = (1-Q) = 0.9981]
Small Optics Suspension (SOS) fails to properly suspend, damp / actuate the Input/Output optical components
SOS1
SOS fails to properly suspend, damp / actuate Mode Cleaner Mirror #2 at WHAM1
SOS12
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Mode Matching Telescope #1 at WHAM1
SOS14
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Fold Mirror #1 at WHAM1
SOS16
SOS:F=0.0003094
LOS11=SOS11=SOS12=SOS13=SOS14=SOS15=SOS16
SOS fails to properly suspend, damp / actuate Mode Cleaner Mirror #1 at WHAM1
SOS11
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Mode Cleaner Mirror #3 at WHAM1
SOS13
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Mode Matching Telescope #2 at WHAM2
SOS15
SOS:F=0.0003094


Unavailability: Q = 1.908e-5
[Availability: A = (1-Q) = 1.0000]
Position Sensor Failures
LOS1121
Position Sensor #1 Fails
LOS11211
Position Sensor #2 Fails
LOS11212
Position Sensor #3 Fails
LOS11213
Position Sensor #4 Fails
LOS11214
Position Sensor #5 Fails
LOS11215
LED fails
LOS11211A
LED:M=3.4698e+008
LED fails
LOS11212A
LED:M=3.4698e+008
LED fails
LOS11213A
LED:M=3.4698e+008
LED fails
LOS11214A
LED:M=3.4698e+008
LED fails
LOS11215A
LED:M=3.4698e+008
Photo Diode fails
LOS11211B
PD:M=1.9952e+007
Photo Diode fails
LOS11212B
PD:M=1.9952e+007
Photo Diode fails
LOS11213B
PD:M=1.9952e+007
Photo Diode fails
LOS11214B
PD:M=1.9952e+007
Photo Diode fails
LOS11215B
PD:M=1.9952e+007


Actuator Failures
Unavailability: Q = 4.360e-7
[Availability: A = (1-Q) = 1.0000]
LOS1122
Actuator #1 Fails
LOS11221
Magnet Fails
LOS11221A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11221C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11221B
BOND:M=2e+009
Coil Fails
LOS11221D
COIL:M=9.009e+009
Actuator #2 Fails
LOS11222
Magnet Fails
LOS11222A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11222C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11222B
BOND:M=2e+009
Coil Fails
LOS11222D
COIL:M=9.009e+009
Actuator #3 Fails
LOS11223
Magnet Fails
LOS11223A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11223C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11223B
BOND:M=2e+009
Coil Fails
LOS11223D
COIL:M=9.009e+009
Actuator #4 Fails
LOS11224
Magnet Fails
LOS11224A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11224C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11224B
BOND:M=2e+009
Coil Fails
LOS11224D
COIL:M=9.009e+009
Actuator #5 Fails
LOS11225
Magnet Fails
LOS11225A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11225C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11225B
BOND:M=2e+009
Coil Fails
LOS11225D
COIL:M=9.009e+009

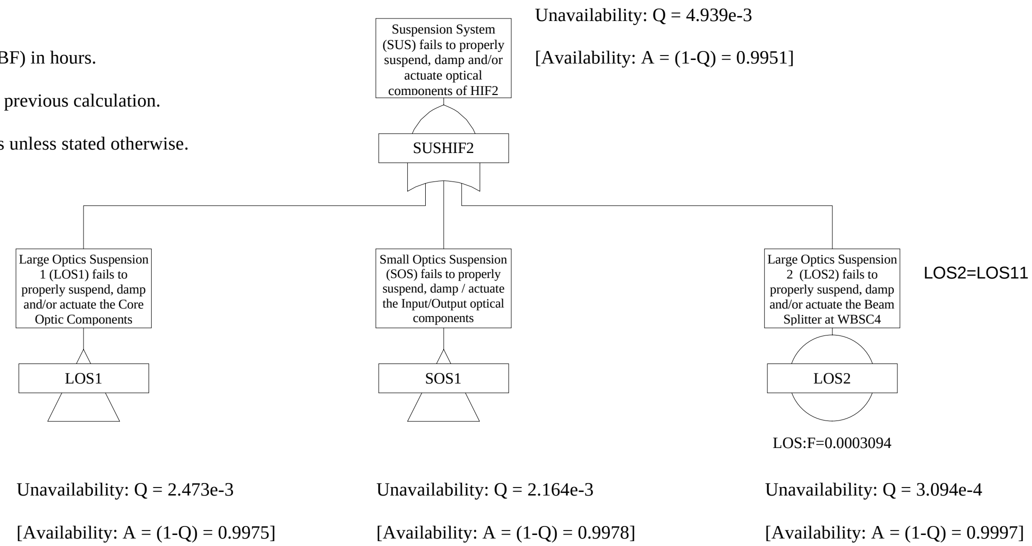
APPENDIX E:
HIF2 SUS
AVAILABILITY PREDICTION

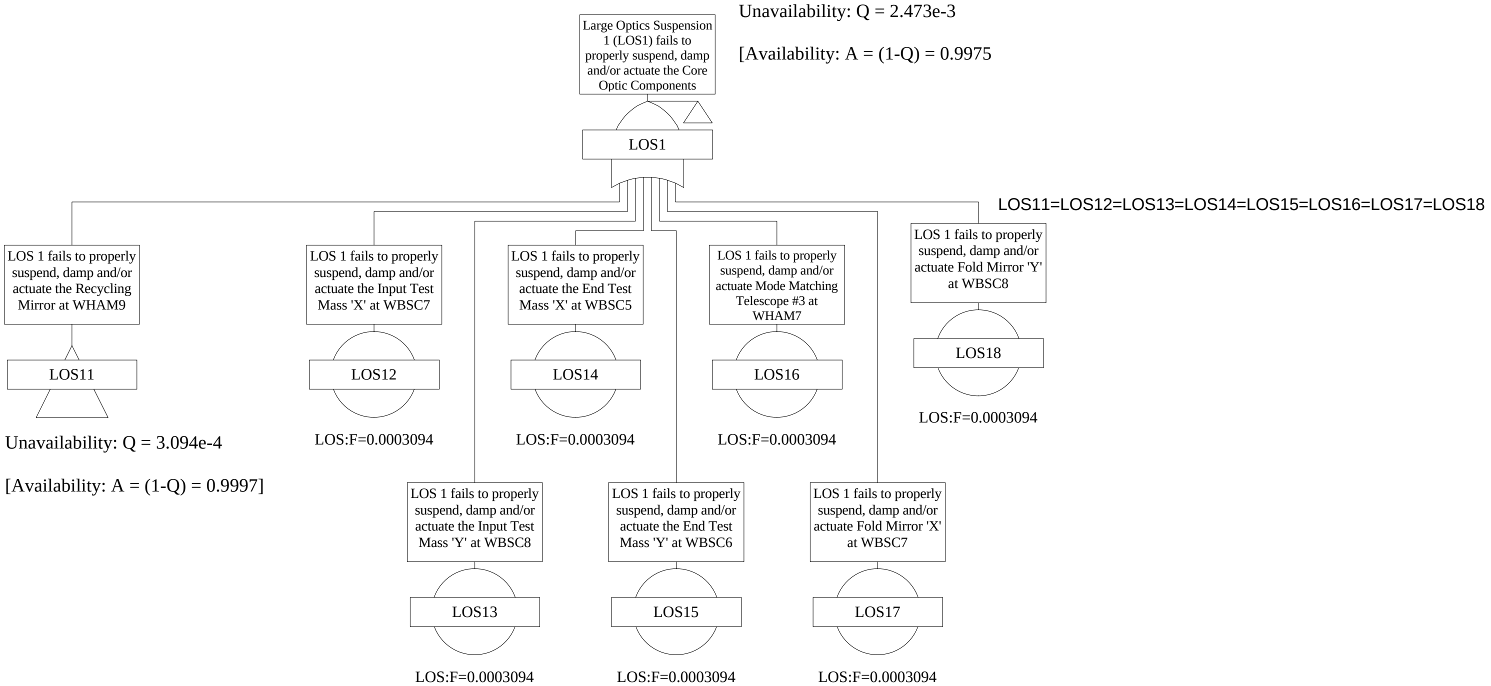
NOTES:

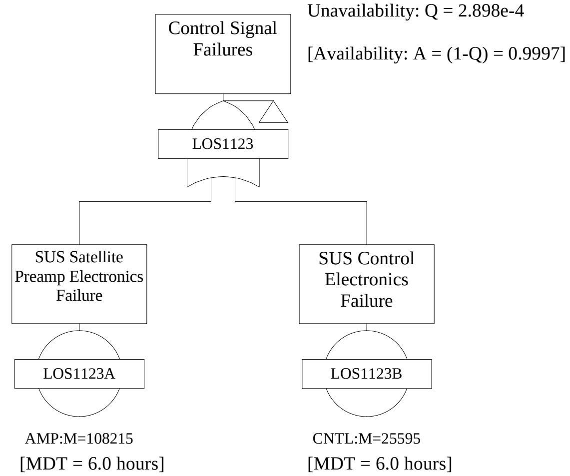
1. M = Mean-Time-Between-Failure (MTBF) in hours.

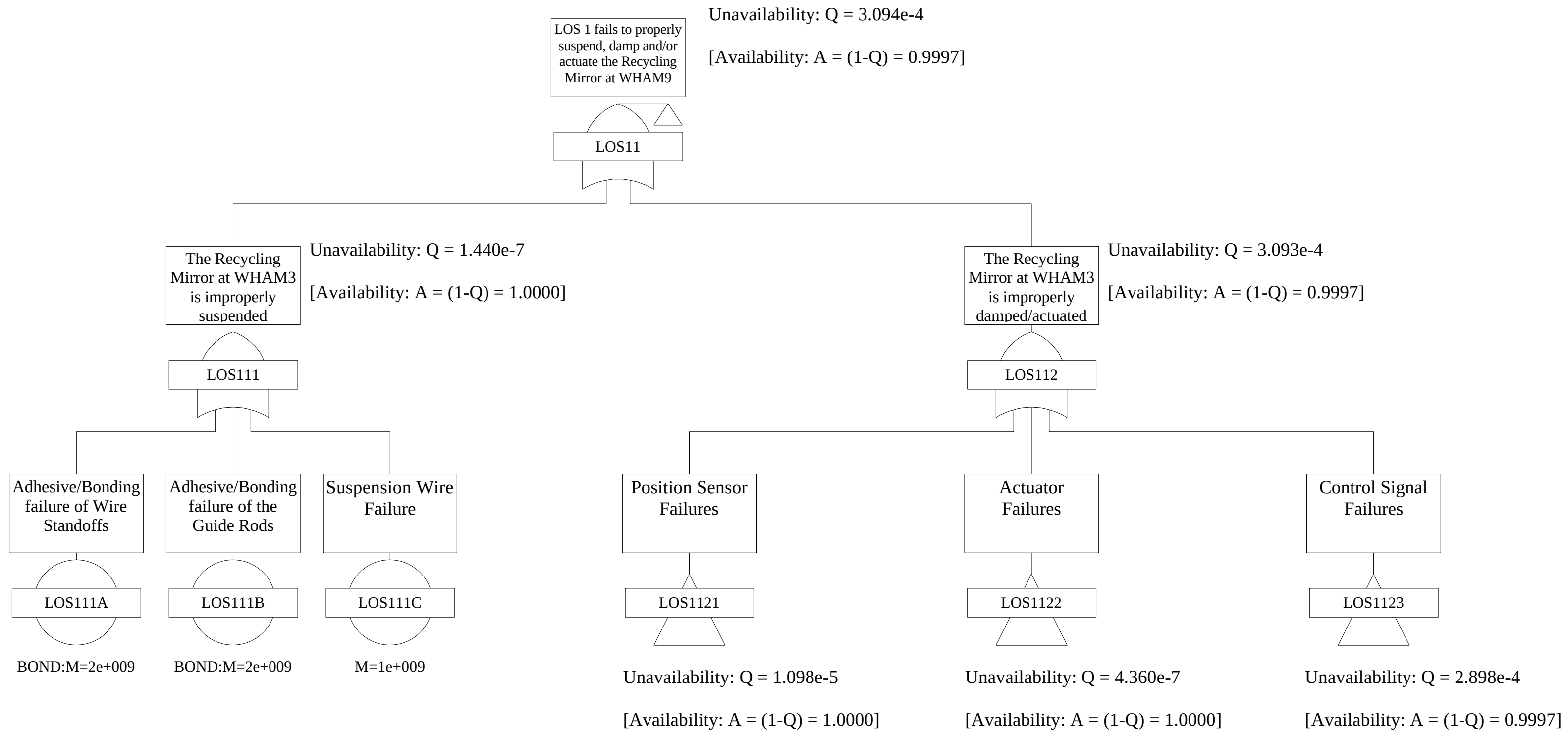
2. F = Fixed Unavailability determined by previous calculation.

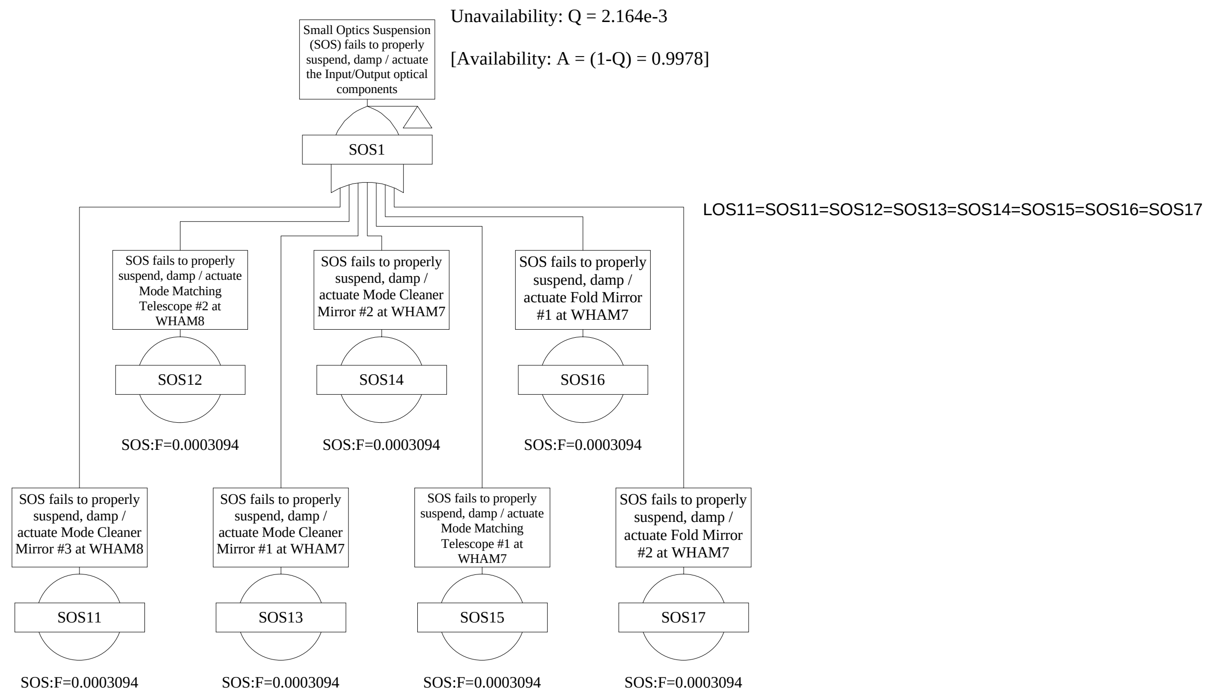
3. MDT = Mean-Down-Time = 72.0 hours unless stated otherwise.

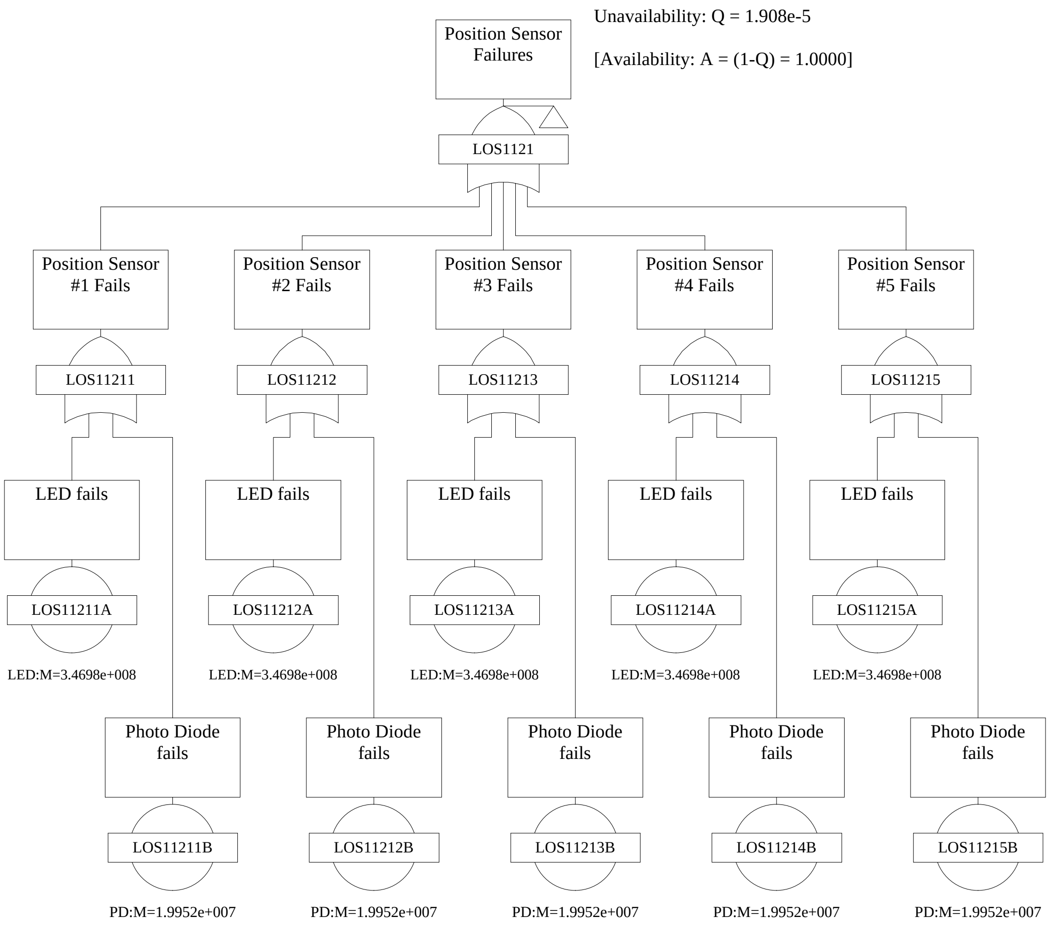


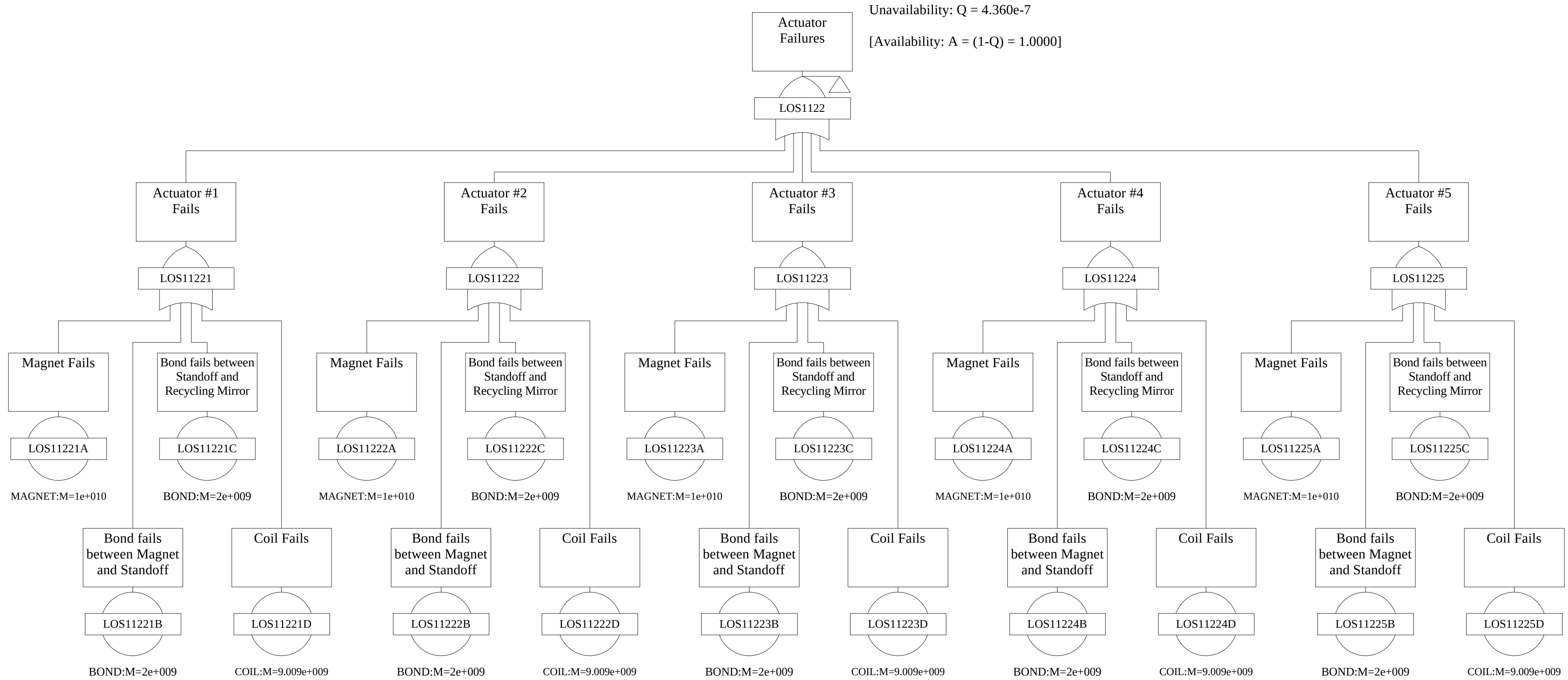

Large Optics Suspension 1 (LOS1) fails to properly suspend, damp and/or actuate the Core Optic Components
Unavailability: Q = 2.473e-3
[Availability: A = (1-Q) = 0.9975]
LOS1
LOS11=LOS12=LOS13=LOS14=LOS15=LOS16=LOS17=LOS18
LOS 1 fails to properly suspend, damp and/or actuate the Recycling Mirror at WHAM9
LOS11
Unavailability: Q = 3.094e-4
[Availability: A = (1-Q) = 0.9997]
LOS 1 fails to properly suspend, damp and/or actuate the Input Test Mass 'X' at WBSC7
LOS12
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate the End Test Mass 'X' at WBSC5
LOS14
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate Mode Matching Telescope #3 at WHAM7
LOS16
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate Fold Mirror 'Y' at WBSC8
LOS18
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate the Input Test Mass 'Y' at WBSC8
LOS13
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate the End Test Mass 'Y' at WBSC6
LOS15
LOS:F=0.0003094
LOS 1 fails to properly suspend, damp and/or actuate Fold Mirror 'X' at WBSC7
LOS17
LOS:F=0.0003094


Control Signal Failures
Unavailability: Q = 2.898e-4
[Availability: A = (1-Q) = 0.9997]
LOS1123
SUS Satellite Preamp Electronics Failure
LOS1123A
AMP:M=108215
[MDT = 6.0 hours]
SUS Control Electronics Failure
LOS1123B
CNTL:M=25595
[MDT = 6.0 hours]

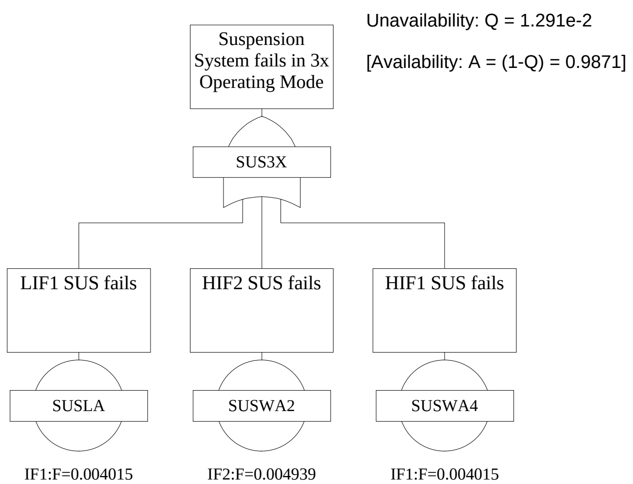

LOS 1 fails to properly suspend, damp and/or actuate the Recycling Mirror at WHAM9
Unavailability: Q = 3.094e-4
[Availability: A = (1-Q) = 0.9997]
LOS11
The Recycling Mirror at WHAM3 is improperly suspended
Unavailability: Q = 1.440e-7
[Availability: A = (1-Q) = 1.0000]
LOS111
The Recycling Mirror at WHAM3 is improperly damped/actuated
Unavailability: Q = 3.093e-4
[Availability: A = (1-Q) = 0.9997]
LOS112
Adhesive/Bonding failure of Wire Standoffs
LOS111A
BOND:M=2e+009
Adhesive/Bonding failure of the Guide Rods
LOS111B
BOND:M=2e+009
Suspension Wire Failure
LOS111C
M=1e+009
Position Sensor Failures
LOS1121
Unavailability: Q = 1.098e-5
[Availability: A = (1-Q) = 1.0000]
Actuator Failures
LOS1122
Unavailability: Q = 4.360e-7
[Availability: A = (1-Q) = 1.0000]
Control Signal Failures
LOS1123
Unavailability: Q = 2.898e-4
[Availability: A = (1-Q) = 0.9997]


Small Optics Suspension (SOS) fails to properly suspend, damp / actuate the Input/Output optical components
Unavailability: Q = 2.164e-3
[Availability: A = (1-Q) = 0.9978]
SOS1
LOS11=SOS11=SOS12=SOS13=SOS14=SOS15=SOS16=SOS17
SOS fails to properly suspend, damp / actuate Mode Matching Telescope #2 at WHAM8
SOS12
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Mode Cleaner Mirror #2 at WHAM7
SOS14
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Fold Mirror #1 at WHAM7
SOS16
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Mode Cleaner Mirror #3 at WHAM8
SOS11
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Mode Cleaner Mirror #1 at WHAM7
SOS13
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Mode Matching Telescope #1 at WHAM7
SOS15
SOS:F=0.0003094
SOS fails to properly suspend, damp / actuate Fold Mirror #2 at WHAM7
SOS17
SOS:F=0.0003094

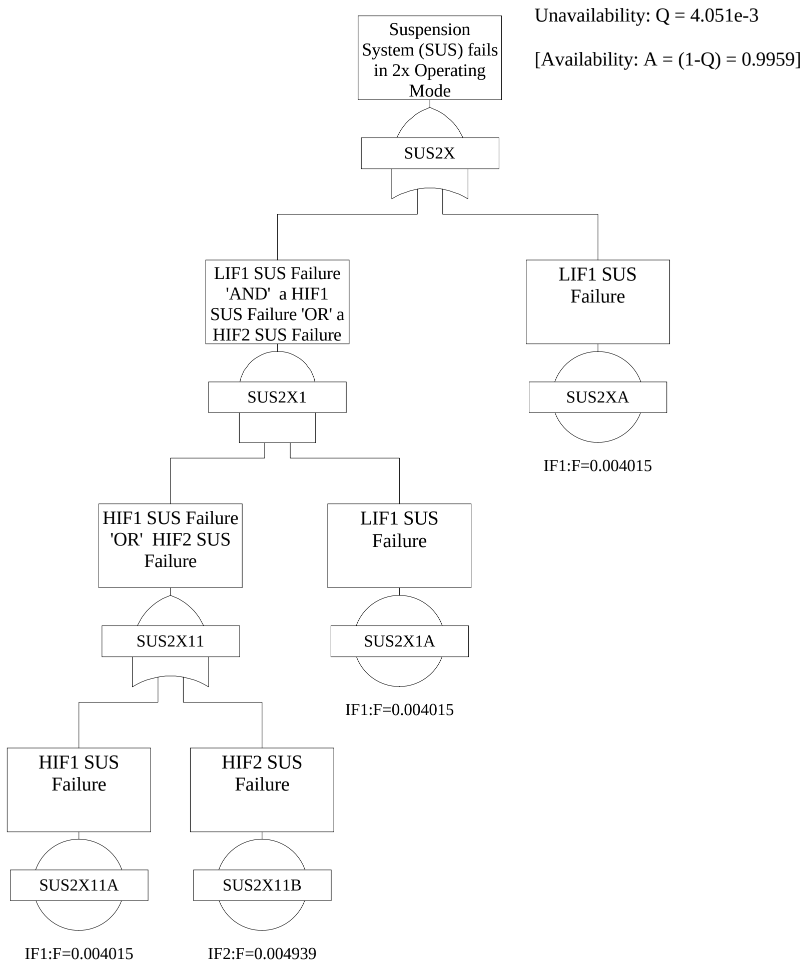

Position Sensor Failures
Unavailability: Q = 1.908e-5
[Availability: A = (1-Q) = 1.0000]
LOS1121
Position Sensor #1 Fails
LOS11211
Position Sensor #2 Fails
LOS11212
Position Sensor #3 Fails
LOS11213
Position Sensor #4 Fails
LOS11214
Position Sensor #5 Fails
LOS11215
LED fails
LOS11211A
LED:M=3.4698e+008
LED fails
LOS11212A
LED:M=3.4698e+008
LED fails
LOS11213A
LED:M=3.4698e+008
LED fails
LOS11214A
LED:M=3.4698e+008
LED fails
LOS11215A
LED:M=3.4698e+008
Photo Diode fails
LOS11211B
PD:M=1.9952e+007
Photo Diode fails
LOS11212B
PD:M=1.9952e+007
Photo Diode fails
LOS11213B
PD:M=1.9952e+007
Photo Diode fails
LOS11214B
PD:M=1.9952e+007
Photo Diode fails
LOS11215B
PD:M=1.9952e+007


Actuator Failures
Unavailability: Q = 4.360e-7
[Availability: A = (1-Q) = 1.0000]
LOS1122
Actuator #1 Fails
LOS11221
Actuator #2 Fails
LOS11222
Actuator #3 Fails
LOS11223
Actuator #4 Fails
LOS11224
Actuator #5 Fails
LOS11225
Magnet Fails
LOS11221A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11221C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11221B
BOND:M=2e+009
Coil Fails
LOS11221D
COIL:M=9.009e+009
Magnet Fails
LOS11222A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11222C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11222B
BOND:M=2e+009
Coil Fails
LOS11222D
COIL:M=9.009e+009
Magnet Fails
LOS11223A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11223C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11223B
BOND:M=2e+009
Coil Fails
LOS11223D
COIL:M=9.009e+009
Magnet Fails
LOS11224A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11224C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11224B
BOND:M=2e+009
Coil Fails
LOS11224D
COIL:M=9.009e+009
Magnet Fails
LOS11225A
MAGNET:M=1e+010
Bond fails between Standoff and Recycling Mirror
LOS11225C
BOND:M=2e+009
Bond fails between Magnet and Standoff
LOS11225B
BOND:M=2e+009
Coil Fails
LOS11225D
COIL:M=9.009e+009

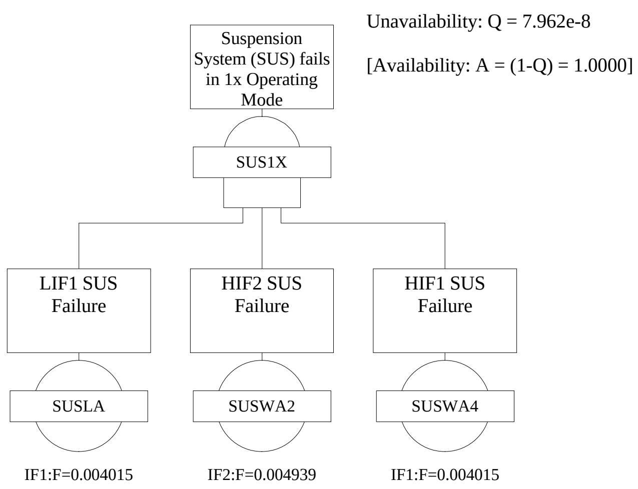
APPENDIX F:
LIGO 3X
SUS AVAILABILITY PREDICTION


Unavailability: Q = 1.291e-2
[Availability: A = (1-Q) = 0.9871]
Suspension System fails in 3x Operating Mode
SUS3X
LIF1 SUS fails
HIF2 SUS fails
HIF1 SUS fails
SUSLA
SUSWA2
SUSWA4
IF1:F=0.004015
IF2:F=0.004939
IF1:F=0.004015

APPENDIX G:
LIGO 2X
SUS AVAILABILITY PREDICTION


Suspension System (SUS) fails in 2x Operating Mode
Unavailability: Q = 4.051e-3
[Availability: A = (1-Q) = 0.9959]
SUS2X
LIF1 SUS Failure 'AND' a HIF1 SUS Failure 'OR' a HIF2 SUS Failure
SUS2X1
LIF1 SUS Failure
SUS2XA
IF1:F=0.004015
HIF1 SUS Failure 'OR' HIF2 SUS Failure
SUS2X11
LIF1 SUS Failure
SUS2X1A
IF1:F=0.004015
HIF1 SUS Failure
SUS2X11A
IF1:F=0.004015
HIF2 SUS Failure
SUS2X11B
IF2:F=0.004939

APPENDIX H:
LIGO 1X
SUS AVAILABILITY PREDICTION


Unavailability: Q = 7.962e-8
[Availability: A = (1-Q) = 1.0000]
Suspension System (SUS) fails in 1x Operating Mode
SUS1X
LIF1 SUS Failure
HIF2 SUS Failure
HIF1 SUS Failure
SUSLA
SUSWA2
SUSWA4
IF1:F=0.004015
IF2:F=0.004939
IF1:F=0.004015