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Production Facility System Reliability Analysis Report

Closed Loop Helium Cooling System
Los Alamos National Laboratory (LANL) Design

Accelerator Production of ^{99}Mo

Prepared by: Crystal Dale & Steven Klein
September 30, 2015

Acronyms and Abbreviations

ANL	Argonne National Laboratory
CLHCS	Closed Loop Helium Cooling System
LANL	Los Alamos National Laboratory
MDT	Mean Down Time
MLDT	Mean Logistics Delay Time
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
P&ID	Piping and Instrumentation Diagram
RBD	Reliability Block Diagram
RMA	Reliability, Maintainability, Availability
SCADA	Supervisory Control and Data Acquisition

1 Summary

1.1 Objective

This document describes the reliability, maintainability, and availability (RMA) modeling of the Los Alamos National Laboratory (LANL) design for the Closed Loop Helium Cooling System (CLHCS) planned for the NorthStar accelerator-based ^{99}Mo production facility. The current analysis incorporates a conceptual helium recovery system, beam diagnostics, and prototype control system into the reliability analysis. The results from the 1000 hr blower test are addressed.

The general methods utilized in the modeling effort are discussed followed by the results of applying those techniques on the specific system. The reliability relationship between equipment is shown by a reliability block diagram (RBD) provided in Appendix C. A steady-state estimate of the RMA performance of the system is provided in analytical form. Consideration of possible effects of multiple operating modes, logistics constraints, variable equipment duty cycles, or similar factors are beyond the scope of this report; however, could be evaluated in a future study using Monte Carlo techniques usually employed for evaluation of those parameters.

1.2 Reliability Model and Results

An analysis of the expected reliability of the Closed Loop Helium Cooling System has been performed. The configuration utilized for the analysis was drawn from the current Piping and Instrumentation Diagram (P&ID) provided in Appendix A, the Production flow loop line diagram provided in Appendix B and a system engineering walk down.

The reliability prediction is an asymptotic steady-state estimate of the Mean-Time-Between-Failure (MTBF) of the system. This estimate is based on techniques described in Mil-Std-217C as interpreted with the PTC Windchill Quality Solutions software, a recognized standard for such computations. The environment selected for the computation was Ground Benign, Controlled, which is typical of a laboratory setting for equipment operation. An average temperature of 30°C was used throughout. The detailed method of computation utilized expected failure of mechanical systems for those types of components and electrical failure distribution for those components. All failure rates used were those reported in the national component reliability database managed by Rome Air Development Center as catalogued by PTC Windchill.

Confirmatory estimates were performed by computations on an Excel Spreadsheet. In addition this utility allowed for an estimate for Mean-Time-to-Repair (MTTR) from engineering judgement for repair (either by actual repair or removal and replacement of the failed item). From this calculation inherent (design) availability was estimated. With the addition of an operating cycle of 156 hours per week uptime (12 hours planned downtime) dormant failures could be estimated providing a means to estimate operational availability. In addition, the techniques in Mil-Std-882 were applied to estimate risk factors and probability of failure on demand typical of system safety considerations, where safety refers to both personnel and equipment.

1.3 Reliability Prediction Summary

PTC Windchill estimates the MTBF of the system to be 649 hours. Details are shown in the Reliability Prediction Summary provided in Appendix D. The SCADA Subsystem is estimated to be the least reliable with an MTBF of 1,177 hours while the Heat Exchanger Subsystem is the most reliable at 20,991 hours MTBF. The SCADA system results are dominated by the failure rates estimated for the pressure transducers and snubbers.

Details down to the level of system component are provided in Appendix E, titled System Tree Summary; part numbers were chosen from the national reliability database, quantity of part type included and the failure rate of each part reported within the database are all catalogued.

The Reliability Prediction Part Type Summary provided in Appendix F provides a breakdown by individual component included in the prediction. The table in Appendix F shows the percent of total system failure rate contributed by each particular part type; number of each type of component is included in this estimate.

1.4 Availability and Safety Prediction Summary

The Excel Spreadsheet provided in Appendix G, presents the estimate of reliability, maintainability, availability and system safety for the system. As noted the reliability portion of the table matches that of PTC Windchill.

The various columns of information are as follows:

1. Nomenclature – the name of the system, subsystem, or component
2. Quantity – number of items in the system
3. NPRD – part number from the national reliability database
4. Item FRPMH – failure rate per million operating hours of the item from the reliability database or accumulated for the subsystem from component values
5. Total FRPMH – failure rate per million operating hours for the item type in that subsystem; here the number of items of each type are accumulated
6. MTBF – Mean-Time-Between-Failure of the item (inverse of FRPMH)
7. MTTR – Mean-Time-To-Repair of the item
8. RRF – repair rate factor, which includes the failure rate estimate for the item and its repair rate
9. Ops/Hrs/Wk – mission profile operating hours per week for the item
10. Uptime Failures – expected failures of the item per operating interval
11. Uptime CM Time – expected corrective maintenance time for each item per operating interval
12. Dormant Failures – expected failures by item during downtime
13. Dormant CM Time – expected corrective maintenance time due to dormant failures; taken at beginning of the next operating cycle
14. Total Failures – both dormant and operating

15. Total CM Time – corrective maintenance time from operating and dormant failures
16. Risk Frequency – from Mil-Std-882 definitions based on accumulated failure rate
17. Severity – from Mil-Std-882 definitions (the system is assumed to offer no personal hazard during operation)
18. PFD – Probability of Failure on Demand, which is in this case the unavailability of the item

Inherent (Ai) and Operational (Ao) availabilities are provided in the table. Inherent availability includes only the operating MTBF and MTTR while operational availability includes all downtime from any source. Computed inherent availability is 0.9982, defined as $MTBF / (MTBF + MTTR)$. Inherent availability is a measure of the design's estimated long term availability of the system under constant failure rate assumptions. The spreadsheet also shows an estimate of the operational availability of 0.9985, which is defined as $Operating\ Time / (Operating\ Time + Corrective\ Maintenance\ Downtime)$. The operational system is unlikely to exhibit an operational availability this high since administrative and logistics downtime is not included. These values would include time waiting for cell access due to radiation dosage limits, downtime associated with diagnostics, and logistics time awaiting spare parts.

Examination of the individual sub-system results in the spreadsheet illustrate that the cooling system represents behavior typical of an electronically controlled mechanical system where the elements with the highest failure rate are electronic (SCADA), whereas those with the longest repair times are mechanical (Heat Exchanger and He Accumulator). Since electronics may be located to provide ease of module repair (generally through item replacement) and may be configured to provide self-diagnostics their impact on overall system availability is likely small. The availability of mechanical systems, however, is dominated by diagnostics and repair time. By their very function, mechanical components are located in the operating environment. With this fact in mind, emphasis must be placed on engineering design for maintenance. Designing for maintenance includes installing diagnostic hardware that provides early indication of wear-out mechanisms and employment of quick disconnect hardware wherever possible to affect rapid repair when necessary.

2 Reliability Testing

A 1000 hour system test was conducted with no failures, allowing for the estimate of system reliability using a one-sided lower confidence limit:

Confidence Level	Estimated MTBF (hrs)
60%	1,091
70%	831
80%	649
90%	434

As engineering testing continues all test hours may be accumulated to improve the statistical analysis of expected reliability. The “no failures” one-sided estimate may likewise be continued in those cases where failures that do occur during testing are analyzed to find root cause and

the design element causing the failure corrected. At that time the failure may be removed from the database.

3 Methodology

Availability is defined as the probability that a system will be operating during the times that it is scheduled to operate. For the purposes of RMA estimation, if only active maintenance time is included, the resulting availability estimate is referred to as inherent Availability (A_i), being a function solely of equipment design and not of any logistics constraints. Where all downtime is included in the estimate, such as waiting for system cool down for access, spare parts, or maintenance personnel, the resulting estimate is referred to as Operational Availability (A_o).

Generally, it is assumed that the statistical distribution of failures of an individual component is exponential. This statement is equivalent to requiring that the equipment failure rate be constant. Hence, infant mortality and aging, including wear out effects, are ignored. This assumption is usually referred to as the steady-state region of equipment life.

Similarly, a constant restoration rate is utilized as an estimate of the time required to return the equipment to an operation status once a failure has occurred.

Following standard convention the constant failure rate is identified by λ and the constant restoration time by τ . For constant values, the inverse of λ is referred to as the Mean-Time-Between-Failure (MTBF). If only active repair time is included in τ its inverse is the Mean-Time-To-Repair (MTTR). Where all downtime is included its inverse is referred to as the Mean-Down-Time (MDT). Where logistics downtime is explicitly used it is referred to as Mean-Logistics-Delay-Time and the MDT for the system is the sum of MTTR and MLDT. Using these symbolic representations we may express availability as:

- Inherent Availability, $A_i = \text{MTBF}/(\text{MTBF} + \text{MTTR})$
- Operational Availability, $A_o = \text{MTBF}/(\text{MTBF} + \text{MDT})$

Hence, an estimate of availability of a system requires an estimate of the MTBF and the MTTR, or MDT, of the system. In practice, these variables are obtained by summation of component failure and repair rates with consideration of the multiplicity of each equipment type and any redundancy that exists. As stated previously, the represented analysis does not include time waiting for cell access due to radiation dosage limits, downtime associated with diagnostics, or logistics time awaiting spare parts, therefore the resulting estimate for A_o will be higher than it would be if all down time were accounted for.

A system consisting of two components, operating independently in series, having failure rates λ_1 and λ_2 exhibits a composite failure rate of the sum of the two failure rates ($\lambda_{\text{sys}} = \lambda_1 + \lambda_2$). This expression may be generalized to an arbitrary number of components by: $\lambda_{\text{sys}} = \sum_{x=1}^n \lambda_n$. In the special case where n components are identical the system failure rate is then simply $n\lambda$.

Computation of the equivalent failure rate of a system consisting of m identical, on line, or operating, redundant components is provided by the integral over all future times of the failure distribution:

$$\int_0^{\infty} \left(\sum_{x=n}^m \frac{m!}{x! (m-x)!} (e^{-\lambda t})^x (1 - e^{-\lambda t})^{m-x} \right) dt$$

Where m is the number of components, n is the number required, and λ is the failure rate. For the single redundancy case, with $m=2$ and $n=1$, the system failure, $MTBF_{sys} = (3/2) MTBF = 1.5MTBF$. For the double redundancy, with $m=3$ and $n=1$, the system failure, $MTBF_{sys} = (11/6) MTBF = 1.8MTBF$. The coefficients for $MTBF$ may simply be computed as $\sum_{x=n}^m \frac{1}{n}$ where m, n are as defined above.

Analytical models provide estimates of the inherent capability of the design and clearly demonstrate the equipment and subsystems that dominate the failure rates and maintenance burden of the system. However, such models are generally incapable of providing much insight into the expected real world operation of the system. In particular, systems containing complex functional redundancy involving different equipment in the redundant paths are often difficult to model in closed form. Similarly, systems that will operate in a variety of modes, subjecting equipment to varying stress levels for differing time periods, cannot readily be examined analytically. Analytical techniques also suffer from the inability to fully handle degraded operating modes. For production systems the ability to operate at lower than optimum production rates is usually a feature of their design. Thus, modeling of the system demands that such modes of operation be examined. This is accomplished through employing techniques that allow specific handling of degraded modes of operation and the rules governing their use. Finally, the impact of logistics constraints such as the availability and quantity of spare parts and maintenance personnel is usually beyond the ability of analytical models to fully assess.

The solution to the need to examine the expected RMA performance of such complex systems operating according to varying mission timelines and logistics constraints is the application of open form solutions such as simulation techniques.

4 System

This section details the system analyzed in the RMA analysis of the CLHCS.

4.1 Closed Loop Helium Cooling System (CLHCS)

The CLHCS is a closed-loop configured, helium-cooling system designed to remove heat from the molybdenum targets during accelerator irradiation. The cooling system is designed to provide ~150 gram/sec of helium to the target at a pressure of 2MPa and temperature of 30°C, for 120 kW of steady state heat removal.

The operational timeline for the production system is based on a weekly run schedule, with an irradiation time of 6.5 days, followed by a 0.5 day (12 hr) down time to change out targets. The operational plan would follow the weekly run pattern for 10 months, followed by 2 months of

maintenance down time. There are 16 accelerators envisioned in the production facility, with each target being simultaneously irradiated by 2 accelerators. There will be 7 accelerator pairs operating at any given time, with 1 pair down for maintenance.

4.2 System Description

The P&ID for the system is shown in Appendix A. In the CLHCS design, a blower contained within a pressurized system is used to pump the helium cooling gas. A three-lobed roots-type blower (Aerzen) with a variable frequency drive motor (WEG) delivers an output pressure of ~ 2.0 MPa. Roots-type blowers are typically characterized by high mass flow rate with fairly low pressure rise, ~ 100 kPa. To achieve the high target inlet pressure of 2 MPa, the blower is enclosed in a pressure vessel that is pressurized very near the desired target inlet pressure. In this fashion, the roots blower is only required to overcome the dynamic pressure losses in the system, which is well within the capabilities of a roots blower.

The pressure vessel housing consists of a 30" diameter Schedule 10 steel pipe with a pipe cap welded to one end. A 30" pipe flange is welded on the other end of the pipe. The blower and motor are enclosed in the pressure vessel by bolting the pipe flange to a 4" thick steel flange plate. The flange plate is welded to a steel floor skid. The blower and motor sit on a 1" steel plate cantilevered off the end of the flange plate. The pressure vessel housing rolls back and forth on rails mounted to the floor skid allowing the system to be opened to access the motor and blower for maintenance. The electrical motor is enclosed within the pressure vessel because it is easier and less expensive to have electrical feed through penetrations instead of a rotating shaft.

The outlet of the blower is connected to a 2" steel pipe that is welded to the flange plate. All of the piping downstream of the pressure vessel is 2" steel pipe. The large pipe diameter allows for low flow velocity and hence low pressure loss in the piping.

From the blower outlet on the pressure vessel, the helium gas is piped to a heat exchanger (plate style) which serves as an after cooler. The helium gas is heated as it is compressed by the blower. The after cooler is used to remove this heat. The helium is then piped to a filter (Xebec) to remove any oil or particulates in the gas. From the filter, the helium is piped to the target. Thermocouples (Omega type K) are installed in the helium gas stream on the inlet and outlet of the target to measure the temperature rise of the helium across the target, which is used to calculate the power removed from the target. There is an Infrared Camera to monitor the target temperature for production as well as an OTR camera to monitor beam position and profile on the beam window. Other beam diagnostics include beam position and beam current monitors.

Downstream of the target, the helium passes through a simple screen filter. The purpose of the screen filter is to trap pieces of target if it were to disassemble during irradiation. From the screen filter, the helium is piped to a second heat exchanger (plate style) which is used to remove the heat absorbed in the helium from the target. Both heat exchangers on the helium flow loop are plate style with facility cooling water on the water side, removing the heat from the helium side. The inlet temperature of the cooling water is ~ 25 °C with a volumetric flow rate of $\sim$

11 gpm. From the exit of the heat exchanger, the helium is piped through a flow meter to measure the mass flow rate of the helium gas in the flow loop. From the flow meter, the helium is piped back into the pressure vessel. System pressure diagnostics are provided by Omega pressure transmitters. A conceptual helium recovery system and prototype control system are included in the analysis.

5 Conclusions

It is a reasonable assumption, based on analysis and testing, that the system will normally exhibit operation without failure during the planned 156 hour operating cycle. In addition, the corrective maintenance time is consistent with the ability to diagnose and repair the system in the 12 hour downtime planned until the next operational cycle. This conclusion is, of course, dependent on three factors being present: (1) sufficient diagnostics to identify failed items or, in the case of mechanical elements, those diagnostics exhibiting characteristics that are known indicators of wear-out and subsequent failure; (2) design-for-maintenance sufficient to allow replacement/repair consistent with the operating environment; (3) availability of spare parts, tools, and similar items necessary to affect the repair.

6 References

1. Reliability, Maintainability, Availability (RMA) Assessment Report for Closed Loop Helium Cooling System, LA-UR-12-25459, September 28, 2012.
2. National Component Reliability Database, managed by Rome Air Development Center, catalogued by PTC Windchill.
3. Mil-Std-217C
4. Mil-Std-882

7 Appendices

Appendix A – Production Facility Helium Flow Loop P&ID

Appendix B – Production Flow Loop Line Diagram

Appendix C – Reliability Block Diagram – Production Closed Loop Helium Cooling System

Appendix D – Reliability Prediction Summary

Appendix E – System Tree Summary

Appendix F – Reliability Prediction Part Type Summary

Appendix G – Analysis Spreadsheet

Appendix A. Production Facility Helium Flow Loop (12/03/14)

Appendix B. Production Flow Loop Line Diagram

CONTRACT N° :

LOCATION:

L1

Main electrical closet

0	10/24/2014	D. Dalmas	
REV.	DATE	NAME	CHANGES
User data 2			

REVISION
0
SCHEME
03

Appendix C: Reliability Block Diagram – Production Closed Loop Helium Cooling System

Equipment Level Diagrams

Failure Rate: 47.638931

MTBF (hrs): 20,991

Temperature: 30

Environment: GB, GC - Ground Benign, Controlled

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Failure Rate: 80.236166

MTBF (hrs): 12,463

Temperature: 30

Environment: GB, GC - Ground Benign, Controlled

Page #:3

Failure Rate: 40.683004

MTBF (hrs): 24,580

Temperature: 30

Environment: GB, GC - Ground Benign, Controlled

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Failure Rate: 32.364904

MTBF (hrs): 30,898

Temperature: 30

Environment: GB, GC - Ground Benign, Controlled

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Appendix D. Reliability Prediction Summary

File Name: CLHCS V3
Assembly:
Ref Des:
Description:

Failure Rate: 849.456769
MTBF (hrs): 1,177
Temperature: 30
Environment: GB, GC - Ground Benign, Controlled

Part Number	Category	Ref Des	Unit Failure Rate	Quantity	Total Failure Rate
NPRD-87249	Switch	Note: Includes all Analog	2.144791	1	2.144791
NPRD-5194	Fuse		0.012418	3	0.037254
NPRD-20114	Accelerometer Assembly		13.991493	2	27.982986
NPRD-20954	Adapter		2.144791	7	15.013537
NPRD-61485	Module		0.460000	1	0.460000
NPRD-73447	Relay		0.519597	16	8.313552
NPRD-37240	Converter		0.072705	3	0.218115
NPRD-31693	Chassis		12.666282	2	25.332564
NPRD-10750	Switch		0.191119	2	0.382238
NPRD-90101	Transducer		46.724605	5	233.623025
NPRD-90101	Transducer		46.724605	2	93.449210
NPRD-81919	Snubber		46.724605	7	327.072235
NPRD-7676	Meter		0.007570	1	0.007570
NPRD-61800	Motor		2.250000	1	2.250000
NPRD-89227	Thermocouple		1.867307	8	14.938456
NPRD-7511	Meter		4.774455	1	4.774455
NPRD-69944	Power Supply		23.362303	1	23.362303
NPRD-22221	Analyzer		23.362303	1	23.362303
NPRD-86578	Switch		46.724605	1	46.724605
NPRD-7676	Meter		0.007570	1	0.007570

Failure Rate: 198.599397

MTBF (hrs): 5,035

Temperature: 30

Environment: GB, GC - Ground Benign, Controlled

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Failure Rate: 290.995274

MTBF (hrs): 3,436

Temperature: 30

Environment: GB, GC - Ground Benign, Controlled

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Appendix E. System Tree Summary

File Name: CLHCS V3
System: System
Ref Des:
Description:

Failure Rate: 1539.974445
MTBF (hrs): 649
Temperature: 30
Environment: GB, GC - Ground Benign, Controlled

Name	Part Number	Ref Des	Quantity	Failure Rate	MTBF
CLHCSV3	System		1	1539.974445	649
Heat Exchanger Subsystem			1	47.638931	20,991
HX-101	NPRD-52556		2	1.808318	553,000
V-200	NPRD-93602		2	1.611174	620,665
External Piping	NPRD-66985		1	2.295147	435,702
Nipples	NPRD-62786		8	13.453112	74,332
Elbows	NPRD-43316		2	4.449962	224,721
Coupling	NPRD-37890		1	1.420521	703,967
Connector	NPRD-34964		1	2.736248	365,464
PRV-201	NPRD-94066		1	15.574868	64,206
Filter	NPRD-46797		1	4.289581	233,123
Target Cooling System			1	80.236166	12,463
Screen Filter	NPRD-46680		1	0.048061	20,806,891
Oil Filter	NPRD-64071		1	46.724605	21,402
Piping (300 psig)	NPRD-66985		1	2.295147	435,702
V-103	NPRD-93733		1	4.469693	223,729
Target Housing	NPRD-54376		1	4.289581	233,123
V-104	NPRD-93733		1	4.469693	223,729
V-105	NPRD-93733		1	4.469693	223,729
V-106	NPRD-93733		1	4.469693	223,729
Scroll Pump	NPRD-8736		1	9.000000	111,111
HE Accumulator System			1	40.683004	24,580
Blower with Motor	NPRD-26041		1	1.220000	819,672
He Pressure Vessel	NPRD-11647		1	18.633540	53,667
Screen Filter	NPRD-46680		1	0.048061	20,806,891
Piping	NPRD-66985		1	2.295147	435,702
PRV	NPRD-94066		1	15.574868	64,206
Power Block	NPRD-69846		1	0.547250	1,827,318
Cable Gland	NPRD-29393		3	0.576735	1,733,899
Motor Feedthrou	NPRD-5097		4	0.400000	2,500,000
Vent Valve	NPRD-94560		1	1.387403	720,771
External Gas Handling System			1	32.364904	30,898
Check Valve	NPRD-92933		1	0.178733	5,594,938
Isolation Valve	NPRD-13021		1	0.112000	8,928,571
2-Stage Pressure Regulator	NPRD-73043		1	2.736248	365,464
Isolation Valve	NPRD-13021		2	0.224000	4,464,286
Purge Valve	NPRD-93829		1	3.624147	275,927
He Supply Bottle	NPRD-88487		2	8.303734	120,428
Bottle Valves	NPRD-93602		2	1.611174	620,665
PRV	NPRD-94066		1	15.574868	64,206
SCADA Subsystem			1	849.456769	1,177
100 Amp Disconnect	NPRD-87249		1	2.144791	466,246
100 Amp Fuse	NPRD-5194		3	0.037254	26,842,755

Appendix E. System Tree Summary

File Name: CLHCS V3
System: NPRD-20114
Ref Des:
Description: w/Power Supply

Failure Rate: 27.982986
MTBF (hrs): 35,736
Temperature:
Environment:

Name	Part Number	Ref Des	Quantity	Failure Rate	MTBF
Accelerometer	NPRD-20114	Note: Includes all Analog	2	27.982986	35,736
Analog I/O	NPRD-20954		7	15.013537	66,607
Digital I/O	NPRD-61485	Note: Includes all Analog	1	0.460000	2,173,913
Relays	NPRD-73447		16	8.313552	120,286
Converter	NPRD-37240		3	0.218115	4,584,737
Chassis	NPRD-31693		2	25.332564	39,475
Interlock Switch	NPRD-10750		2	0.382238	2,616,171
Transducers	NPRD-90101		5	233.623025	4,280
DP Transducers	NPRD-90101		2	93.449210	10,701
Snubber	NPRD-81919		7	327.072235	3,057
Water Flow Meter	NPRD-7676		1	0.007570	132,100,396
VFD	NPRD-61800		1	2.250000	444,444
Thermocouple	NPRD-89227		8	14.938456	66,941
Flow Meter	NPRD-7511		1	4.774455	209,448
UPS	NPRD-69944		1	23.362303	42,804
RGA	NPRD-22221		1	23.362303	42,804
Ethernet Switch	NPRD-86578		1	46.724605	21,402
FS-201	NPRD-7676		1	0.007570	132,100,396
Beam Diagnostics			1	198.599397	5,035
Infrared Camera	NPRD-30060		1	46.724605	21,402
OTR Camera	NPRD-30083		1	135.457304	7,382
BCM	NPRD-61662		4	5.472496	182,732
BPM	NPRD-55460		4	10.944992	91,366
He Recovery Skid			1	290.995274	3,436
Valves	NPRD-93733		9	40.227237	24,859
Vacuum Pump Unit	NPRD-92542		1	46.724605	21,402
Holding Tank	NPRD-88487		1	4.151867	240,855
2-Stage Metal	NPRD-2422		1	0.768979	1,300,426
O-2 Getter	NPRD-49215		1	0.912083	1,096,391
Tritium Getter	NPRD-49215		1	0.912083	1,096,391
Quick Release	NPRD-3047		2	10.400000	96,154
Transducers	NPRD-90101		4	186.898420	5,351

Appendix F. Reliability Prediction Part Type Summary

Project: CLHCS V3

Category	Subcategory	Part Type Failure Rate	% of Total Failure Rate	Part Type Qty	% of Total Qty
Accelerometer	General	27.982986	1.8	2	1.3
Assembly					
Adapter	Electric	15.013537	1.0	7	4.7
Analyzer	Gas	23.362303	1.5	1	0.7
Blower	With Motor	1.220000	0.1	1	0.7
Cable	Lead	0.576735	0.0	3	2.0
Camera	Monochrome	46.724605	3.0	1	0.7
	Video	135.457304	8.8	1	0.7
Chassis	Electrical	25.332564	1.6	2	1.3
Compressor	Air	0.768979	0.0	1	0.7
Connector	Hose	2.736248	0.2	1	0.7
	Quick Disconnect,Adapter	10.400000	0.7	2	1.3
Converter	Signal	0.218115	0.0	3	2.0
Coupling	Pipe	1.420521	0.1	1	0.7
Elbow	Pipe	4.449962	0.3	2	1.3
Filter	Screen,Wire	0.096122	0.0	2	1.3
	Water	4.289581	0.3	1	0.7
Fitting	Mechanical	0.400000	0.0	4	2.7
Fuse	General	0.037254	0.0	3	2.0
Gas Purge System	General	1.824166	0.1	2	1.3
Heat Exchanger	General	1.808318	0.1	2	1.3
Housing	Inlet,Gas	4.289581	0.3	1	0.7
Indicator	Position	10.944992	0.7	4	2.7
Meter	Flow	4.774455	0.3	1	0.7
	Water	0.015140	0.0	2	1.3
Module	Digital	0.460000	0.0	1	0.7
Monitor	Electrical Power	5.472496	0.4	4	2.7
Motor	Blower	2.250000	0.1	1	0.7
Nipple	Pipe	13.453112	0.9	8	5.4
Oil Filters	General	46.724605	3.0	1	0.7
Pipe	Metallic (Summary)	6.885441	0.4	3	2.0
Power Divider	General	0.547250	0.0	1	0.7
Power Supply	UPS	23.362303	1.5	1	0.7
Pump	Pneumatic,Vacuum	9.000000	0.6	1	0.7
Regulator	Pressure,External Tank	2.736248	0.2	1	0.7
Relay	Solid State,Electronic	8.313552	0.5	16	10.7
Snubber	Pressure	327.072235	21.2	7	4.7
Switch	Ethernet,16-Port	46.724605	3.0	1	0.7
	Interlock	0.382238	0.0	2	1.3
	Safety	2.144791	0.1	1	0.7
Tank	Pressure Vessel	18.633540	1.2	1	0.7
	Pressurized,Gas	12.455601	0.8	3	2.0
Thermocouple	(Summary)	14.938456	1.0	8	5.4
Transducer	Pressure	513.970655	33.4	11	7.4

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Appendix G. Analysis Spreadsheet

Quantity	NPRD	Item	Total	MTBF	MTTR	RRF	OpsHrs/Wk	Uptime	Uptime	Dormant	Dormant	Total	Total CM	Risk			
		FRPMH	FRPMH					Failures	CM Time	Failures	CM Time	Failures	Time	y (MIL-STD-882)	Severity (MIL-STD-882)	Overall Risk (MIL-STD-882)	PFD (UAI)
1	Ai:	0.9982	1,539.9745	649	1.20	1.84E-03		1.98E-01	2.30E-01	1.85E-04	2.21E-04	1.99E-01	2.31E-01	5		1 Medium	1.84E-03
1	Ao:	0.9985	47.6389	20,991	2.14	1.02E-04	156.00	7.43E-03	1.59E-02	5.72E-06	1.23E-05	7.44E-03	1.59E-02	3		1 Low	1.02E-04
2	52556	0.9042	1.8083	1,106,000	8.00	1.45E-05	156.00	2.82E-04	2.26E-03	2.17E-07	1.74E-06	2.82E-04	2.26E-03	2		1 Low	7.23E-06
2	93602	0.8056	1.6112	1,241,331	2.50	4.03E-06	156.00	2.51E-04	6.28E-04	1.93E-07	4.83E-07	2.52E-04	6.29E-04	2		1 Low	2.01E-06
1	66985	2.2951	2.2951	435,702	8.00	1.84E-05	156.00	3.58E-04	2.86E-03	2.75E-07	2.20E-06	3.58E-04	2.87E-03	2		1 Low	1.84E-05
0	93602	0.3222	-	3,103,325	2.50	0.00E+00	156.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1		1 Low	8.06E-07
8	62786	1.6816	13.4531	594,658	1.00	1.35E-05	156.00	2.10E-03	2.10E-03	1.61E-06	1.61E-06	2.10E-03	2.10E-03	3		1 Low	1.68E-06
2	43316	2.2250	4.4500	449,442	1.00	4.45E-06	156.00	6.94E-04	6.94E-04	5.34E-07	5.34E-07	6.95E-04	6.95E-04	2		1 Low	2.22E-06
1	37890	1.4205	1.4205	703,967	1.00	1.42E-06	156.00	2.22E-04	2.22E-04	1.70E-07	1.70E-07	2.22E-04	2.22E-04	2		1 Low	1.42E-06
1	34964	2.7362	2.7362	365,464	1.00	2.74E-06	156.00	4.27E-04	4.27E-04	3.28E-07	3.28E-07	4.27E-04	4.27E-04	2		1 Low	2.74E-06
1	94066	15.5749	15.5749	64,206	2.50	3.89E-05	156.00	2.43E-03	6.07E-03	1.87E-06	4.67E-06	2.43E-03	6.08E-03	3		1 Low	3.89E-05
0	52556	0.9042	-	1,106,000	8.00	0.00E+00	156.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1		1 Low	7.23E-06
1	46797	4.2896	4.2896	233,123	1.00	4.29E-06	156.00	6.69E-04	6.69E-04	5.15E-07	5.15E-07	6.70E-04	6.70E-04	2		1 Low	4.29E-06
1			80.2362	12,463	1.89	1.51E-04		1.25E-02	2.36E-02	9.63E-06	1.82E-05	1.25E-02	2.36E-02	4		1 Low	1.51E-04
1	46680	0.0481	0.0481	20,806,891	1.00	4.81E-08	156.00	7.50E-06	7.50E-06	5.77E-09	5.77E-09	7.50E-06	7.50E-06	1		1 Low	4.81E-08
1	64071	46.7246	46.7246	21,402	1.00	4.67E-05	156.00	7.29E-03	7.29E-03	5.61E-06	5.61E-06	7.29E-03	7.29E-03	3		1 Low	4.67E-05
1	66985	2.2951	2.2951	435,702	8.00	1.84E-05	156.00	3.58E-04	2.86E-03	2.75E-07	2.20E-06	3.58E-04	2.87E-03	2		1 Low	1.84E-05
1	93733	4.4697	4.4697	223,729	1.50	6.70E-06	156.00	6.97E-04	1.05E-03	5.36E-07	8.05E-07	6.98E-04	1.05E-03	2		1 Low	6.70E-06
1	54376	4.2896	4.2896	233,123	8.00	3.43E-05	156.00	6.69E-04	5.35E-03	5.15E-07	4.12E-06	6.70E-04	5.36E-03	2		1 Low	3.43E-05
1	93733	4.4697	4.4697	223,729	1.50	6.70E-06	156.00	6.97E-04	1.05E-03	5.36E-07	8.05E-07	6.98E-04	1.05E-03	2		1 Low	6.70E-06
1	93733	4.4697	4.4697	223,729	1.50	6.70E-06	156.00	6.97E-04	1.05E-03	5.36E-07	8.05E-07	6.98E-04	1.05E-03	2		1 Low	6.70E-06
1	93733	4.4697	4.4697	223,729	1.50	6.70E-06	156.00	6.97E-04	1.05E-03	5.36E-07	8.05E-07	6.98E-04	1.05E-03	2		1 Low	6.70E-06
1	8736	9.0000	9.0000	111,111	2.80	2.52E-05	156.00	1.40E-03	3.93E-03	1.08E-06	3.02E-06	1.41E-03	3.93E-03	3		1 Low	2.52E-05
1			40.6830	24,580	2.54	1.03E-04		6.35E-03	1.61E-02	4.88E-06	1.24E-05	6.35E-03	1.61E-02	3		1 Low	1.03E-04
1	26041	1.2200	1.2200	819,672	8.00	9.76E-06	156.00	1.90E-04	1.52E-03	1.46E-07	1.17E-06	1.90E-04	1.52E-03	2		1 Low	9.76E-06
1	11647	18.6335	18.6335	53,667	3.00	5.59E-05	156.00	2.91E-03	8.72E-03	2.24E-06	6.71E-06	2.91E-03	8.73E-03	3		1 Low	5.59E-05
1	46680	0.0481	0.0481	20,806,891	1.00	4.81E-08	156.00	7.50E-06	7.50E-06	5.77E-09	5.77E-09	7.50E-06	7.50E-06	1		1 Low	4.81E-08
1	66985	2.2951	2.2951	435,702	8.00	1.84E-05	156.00	3.58E-04	2.86E-03	2.75E-07	2.20E-06	3.58E-04	2.87E-03	2		1 Low	1.84E-05
1	94066	15.5749	15.5749	64,206	1.00	1.56E-05	156.00	2.43E-03	2.43E-03	1.87E-06	1.87E-06	2.43E-03	2.43E-03	3		1 Low	1.56E-05
1	60846	0.5473	0.5473	1,827,318	1.00	5.47E-07	156.00	8.54E-05	8.54E-05	6.57E-08	6.57E-08	8.54E-05	8.54E-05	1		1 Low	5.47E-07
3	29393	0.1922	0.5767	5,201,696	1.00	5.77E-07	156.00	9.00E-05	9.00E-05	6.92E-08	6.92E-08	9.00E-05	9.00E-05	1		1 Low	1.92E-07
4	5097	0.1000	0.4000	10,000,000	1.00	4.00E-07	156.00	6.24E-05	6.24E-05	4.80E-08	4.80E-08	6.24E-05	6.24E-05	1		1 Low	1.00E-07
1	94560	1.3874	1.3874	720,757	1.50	2.08E-06	156.00	2.16E-04	3.25E-04	1.66E-07	2.50E-07	2.17E-04	3.25E-04	2		1 Low	2.08E-06
0	49454	0.2040	-	4,901,961	1.00	0.00E+00	156.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1		1 Low	2.04E-07
1			32.3649	30,898	1.28	4.14E-05		5.05E-03	6.45E-03	3.88E-06	4.96E-06	5.05E-03	6.46E-03	3		1 Low	4.14E-05
1	92933	0.1787	0.1787	5,594,938	1.50	2.68E-07	156.00	2.79E-05	4.18E-05	2.14E-08	3.22E-08	2.79E-05	4.19E-05	1		1 Low	2.68E-07
1	13021	0.1120	0.1120	8,928,571	2.50	2.80E-07	156.00	1.75E-05	4.37E-05	1.34E-08	3.36E-08	1.75E-05	4.37E-05	1		1 Low	2.80E-07
1	73043	2.7362	2.7362	365,464	1.20	3.28E-06	156.00	4.27E-04	5.12E-04	3.28E-07	3.94E-07	4.27E-04	5.13E-04	2		1 Low	3.28E-06
2	13021	0.1120	0.2240	8,928,571	2.50	5.60E-07	156.00	3.49E-05	8.74E-05	2.69E-08	6.72E-08	3.50E-05	8.74E-05	1		1 Low	2.80E-07
1	93829	3.6241	3.6241	275,927	2.50	9.06E-06	156.00	5.65E-04	1.41E-03	4.35E-07	1.09E-06	5.66E-04	1.41E-03	2		1 Low	9.06E-06
0	13021	0.0224	-	44,642,857	2.50	0.00E+00	156.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1		1 Low	5.60E-08
2	88487	4.1519	8.3037	240,855	1.00	8.30E-06	156.00	1.30E-03	1.30E-03	9.96E-07	9.96E-07	1.30E-03	1.30E-03	3		1 Low	4.15E-06
2	93602	0.8056	1.6112	1,241,331	2.50	4.03E-06	156.00	2.51E-04	6.28E-04	1.93E-07	4.83E-07	2.52E-04	6.29E-04	2		1 Low	2.01E-06
0	49454	0.2040	-	4,901,961	1.00	0.00E+00	156.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1		1 Low	2.04E-07
1	94066	15.5749	15.5749	64,206	1.00	1.56E-05	156.00	2.43E-03	2.43E-03	1.87E-06	1.87E-06	2.43E-03	2.43E-03	3		1 Low	1.56E-05
0	94970	2.7983	-	357,360	1.50	0.00E+00	156.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1		1 Low	4.20E-06

Appendix G. Analysis Spreadsheet

Quantity	NPRD	Item	Total	MTBF	MTTR	RRF	OpsHrs/Wk	Uptime	Uptime	Dormant	Dormant	Total	Total CM	Risk Frequency (MIL-STD-882)	Severity (MIL-STD-882)	Overall Risk (MIL-STD-882)	PFD (UAI)
		FRPMH	FRPMH					Failures	CM Time	Failures	CM Time	Failures	Time				
			849.4568	1,177	1.00	8.50E-04		1.33E-01	1.33E-01	1.02E-04	1.02E-04	1.33E-01	1.33E-01	5		1 Medium	8.49E-04
1	87249	2.1448	2.1448	466,246	1.00	2.14E-06	156.00	3.35E-04	3.35E-04	2.57E-07	2.57E-07	3.35E-04	3.35E-04	2		1 Low	2.14E-06
3	5194	0.0124	0.0373	80,528,265	1.00	3.73E-08	156.00	5.81E-06	5.81E-06	4.47E-09	4.47E-09	5.82E-06	5.82E-06	1		1 Low	1.24E-08
2	20114	13.9915	27.9830	71,472	1.00	2.80E-05	156.00	4.37E-03	4.37E-03	3.36E-06	3.36E-06	4.37E-03	4.37E-03	3		1 Low	1.40E-05
7	20954	2.1448	15.0135	466,246	1.00	1.50E-05	156.00	2.34E-03	2.34E-03	1.80E-06	1.80E-06	2.34E-03	2.34E-03	3		1 Low	2.14E-06
1	61485	0.4600	0.4600	2,173,913	1.00	4.60E-07	156.00	7.18E-05	7.18E-05	5.52E-08	5.52E-08	7.18E-05	7.18E-05	1		1 Low	4.60E-07
16	73447	0.5196	8.3136	1,924,568	1.00	8.31E-06	156.00	1.30E-03	1.30E-03	9.98E-07	9.98E-07	1.30E-03	1.30E-03	3		1 Low	5.20E-07
3	37240	0.0727	0.2181	13,754,212	1.00	2.18E-07	156.00	3.40E-05	3.40E-05	2.62E-08	2.62E-08	3.41E-05	3.41E-05	1		1 Low	7.27E-08
2	31693	12.6663	25.3326	78,950	1.00	2.53E-05	156.00	3.95E-03	3.95E-03	3.04E-06	3.04E-06	3.95E-03	3.95E-03	3		1 Low	1.27E-05
2	10750	0.1911	0.3822	5,232,342	1.00	3.82E-07	156.00	5.96E-05	5.96E-05	4.59E-08	4.59E-08	5.97E-05	5.97E-05	1		1 Low	1.91E-07
5	90101	46.7246	233.6230	21,402	1.00	2.34E-04	156.00	3.64E-02	3.64E-02	2.80E-05	2.80E-05	3.65E-02	3.65E-02	4		1 Low	4.67E-05
2	90101	46.7246	93.4492	21,402	1.00	9.34E-05	156.00	1.46E-02	1.46E-02	1.12E-05	1.12E-05	1.46E-02	1.46E-02	4		1 Low	4.67E-05
7	81919	46.7246	327.0722	21,402	1.00	3.27E-04	156.00	5.10E-02	5.10E-02	3.92E-05	3.92E-05	5.11E-02	5.11E-02	4		1 Low	4.67E-05
1	7676	0.0076	0.0076	132,100,396	1.00	7.57E-09	156.00	1.18E-06	1.18E-06	9.08E-10	9.08E-10	1.18E-06	1.18E-06	1		1 Low	7.57E-09
1	61800	2.2500	2.2500	444,444	1.20	2.70E-06	156.00	3.51E-04	4.21E-04	2.70E-07	3.24E-07	3.51E-04	4.22E-04	2		1 Low	2.70E-06
8	89227	1.8673	14.9385	535,531	1.00	1.49E-05	156.00	2.33E-03	2.33E-03	1.79E-06	1.79E-06	2.33E-03	2.33E-03	3		1 Low	1.87E-06
1	7511	4.7745	4.7745	209,448	1.00	4.77E-06	156.00	7.45E-04	7.45E-04	5.73E-07	5.73E-07	7.45E-04	7.45E-04	2		1 Low	4.77E-06
1	69944	23.3623	23.3623	42,804	1.00	2.34E-05	156.00	3.64E-03	3.64E-03	2.80E-06	2.80E-06	3.65E-03	3.65E-03	3		1 Low	2.34E-05
1	22221	23.3623	23.3623	42,804	1.00	2.34E-05	156.00	3.64E-03	3.64E-03	2.80E-06	2.80E-06	3.65E-03	3.65E-03	3		1 Low	2.34E-05
1	86578	46.7246	46.7246	21,402	1.00	4.67E-05	156.00	7.29E-03	7.29E-03	5.61E-06	5.61E-06	7.29E-03	7.29E-03	3		1 Low	4.67E-05
1	7676	0.0076	0.0076	132,100,396	1.00	7.57E-09	156.00	1.18E-06	1.18E-06	9.08E-10	9.08E-10	1.18E-06	1.18E-06	1		1 Low	7.57E-09
			198.5994	5,035	1.00	1.99E-04		3.10E-02	3.10E-02	2.38E-05	2.38E-05	3.10E-02	3.10E-02	4		1 Low	1.99E-04
1	30060	46.7246	46.7246	21,402	1.00	4.67E-05	156.00	7.29E-03	7.29E-03	5.61E-06	5.61E-06	7.29E-03	7.29E-03	3		1 Low	4.67E-05
1	30083	135.4573	135.4573	7,382	1.00	1.35E-04	156.00	2.11E-02	2.11E-02	1.63E-05	1.63E-05	2.11E-02	2.11E-02	4		1 Low	1.35E-04
4	61662	1.3681	5.4725	730,928	1.00	5.47E-06	156.00	8.54E-04	8.54E-04	6.57E-07	6.57E-07	8.54E-04	8.54E-04	2		1 Low	1.37E-06
4	55460	2.7362	10.9450	365,464	1.00	1.09E-05	156.00	1.71E-03	1.71E-03	1.31E-06	1.31E-06	1.71E-03	1.71E-03	3		1 Low	2.74E-06
			290.9953	3,436	1.36	3.95E-04		3.49E-03	4.74E-03	3.49E-05	4.74E-05	3.53E-03	4.79E-03	3		1 Low	3.95E-04
9	93733	4.4697	40.2272	223,729	1.50	6.03E-05	12.00	4.83E-04	7.24E-04	4.83E-06	7.24E-06	4.88E-04	7.31E-04	2		1 Low	6.70E-06
1	92542	46.7246	46.7246	21,402	2.80	1.31E-04	12.00	5.61E-04	1.57E-03	5.61E-06	1.57E-05	5.66E-04	1.59E-03	2		1 Low	1.31E-04
1	88487	4.1519	4.1519	240,855	1.00	4.15E-06	12.00	4.98E-05	4.98E-05	4.98E-07	4.98E-07	5.03E-05	5.03E-05	1		1 Low	4.15E-06
1	2422	0.7690	0.7690	1,300,426	1.00	7.69E-07	12.00	9.23E-06	9.23E-06	9.23E-08	9.23E-08	9.32E-06	9.32E-06	1		1 Low	7.69E-07
1	49215	0.9121	0.9121	1,096,391	1.00	9.12E-07	12.00	1.09E-05	1.09E-05	1.09E-07	1.09E-07	1.11E-05	1.11E-05	1		1 Low	9.12E-07
1	49215	0.9121	0.9121	1,096,391	1.00	9.12E-07	12.00	1.09E-05	1.09E-05	1.09E-07	1.09E-07	1.11E-05	1.11E-05	1		1 Low	9.12E-07
2	3047	5.2000	10.4000	192,308	1.00	1.04E-05	12.00	1.25E-04	1.25E-04	1.25E-06	1.25E-06	1.26E-04	1.26E-04	2		1 Low	5.20E-06
4	90101	46.7246	186.8984	21,402	1.00	1.87E-04	12.00	2.24E-03	2.24E-03	2.24E-05	2.24E-05	2.27E-03	2.27E-03	3		1 Low	4.67E-05