A COMPREHENSIVE RELIABILITY METHODOLOGY FOR ASSESSING RISK OF REUSING FAILED HARDWARE WITHOUT CORRECTIVE ACTIONS WITH AND WITHOUT REDUNDANCY

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Abstract: *This paper deals with the development of a reliability methodology to assess the consequences of using hardware, without failure analysis or corrective action, that has previously demonstrated that it did not perform per specification. The subject of this paper arose from the need to provide a detailed probabilistic analysis to calculate the change in probability of failures with respect to the base or non-failed hardware.*

The methodology used for the analysis is primarily based on principles of Monte Carlo simulation. The random variables in the analysis are: Maximum Time of Operation (MTO), and

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Operation Time of each Unit (OTU). The failure of a unit is considered to happen if OTU is less than MTO for the Normal Operational Period (NOP) in which this unit is used. NOP as a whole uses a total of 4 units. Two cases are considered. In the first specialized scenario, the failure of any operation or system failure is considered to happen if any of the units used during the NOP fail. In the second specialized scenario, the failure of any operation or system failure is considered to happen only if any two of the units used during the NOP fail together. The probability of failure of the units and the system as a whole is determined for 3 kinds of systems - Perfect System, Imperfect System 1 and Imperfect System 2. In a Perfect System, the operation time of the failed unit is the same as that of the MTO. In an Imperfect System 1, the operation time of the failed unit is assumed as 1% of the MTO. In an Imperfect System 2, the operation time of the failed unit is assumed as zero. In addition, simulated operation time of failed units is assumed as 10% of the corresponding units before zero value. Monte Carlo simulation analysis is used for this study. Necessary software has been developed as part of this study to perform the reliability calculations.

The results of the analysis showed that the predicted change in failure probability (P_F) for the previously failed units is as high as 49% above the baseline (perfect system) for the worst case. The predicted change in system P_F for the previously failed units is as high as 36% for single unit failure without any redundancy. For redundant systems, with dual unit failure, the predicted change in P_F for the previously failed units is as high as 16%. These results will help management to make decisions regarding the consequences of using previously failed units without adequate failure analysis or corrective action.

INTRODUCTION

The subject of this paper arose from a situation experienced under operational conditions. A hardware unit failed to perform per specification under certain cryogenic conditions. When the unit was removed from service and ground tested, the unit also failed to operate per specifications during a specific temperature range. Similarly, in another operation situation, a unit failed to operate under similar circumstances. To duplicate the operational scenario, cryogenic testing was performed and both units failed to close in the temperature range of -60° to -80° F. But, both units would actuate if the energization switch were held (energized) for a long period of time rather than actuated momentarily. The units operated nominally under room temperature conditions and at cryogenic temperature conditions above and below the -60° to -80° F range. In addition, another similar unit failed to operate in the -60° to -80° F temperature range during an acceptance test procedure (ATP) following manufacturing. In all, three units failed to operate nominally in a narrow temperature range but did operate when energized longer than normal. One option considered was to return all three units for operational use since the range in which failures had been experienced were very narrow. This option necessitated the development of a reliability methodology to assess the consequences of operating with known failed hardware such as the ones discussed above. It is the conclusion of this study that these units have a high probability of failing again without adequate failure analysis or corrective action. The reason being that continuous energization of the unit does not constitute an effective workaround for the non-conformance of these units. The object of this paper is to define the methodology developed and used to calculate the change in probability of failures with respect to the base or non-failed hardware for the detailed probabilistic analysis. This work is an extension of the previous work by Mikula, et al. [1] dealing with single unit failure.

BRIEF LITERATURE REVIEW

Principles of probabilistic analysis have been used extensively for solution of practical problems for the last two decades. Freudenthal [2], Cornell [3], Hasofer and Lind [4], and Ang [5] have done fundamental work in this direction. Freudenthal [2] mainly discussed the safety aspect of a member subjected to variable random load. Cornell [3] dealt with the concept of a code, which is probability-based instead of the traditional deterministic code. Hasofer and Lind [4] defined the reliability index as the shortest distance to the failure surface. Ang [5] mainly dealt with the structural risk analysis aspects using the reliability basis. There have been many applications of these fundamental concepts to various practical problems. Some of the noteworthy applications are: Ravindra and Galambos [6], Rackwitz and Fiessler [7], Ellyin and Putcha [8], MacGregor, et al. [9], Putcha [10], Ellingwood, et al. [11], and Ayyub and Haldar [12] to name a few. Much of the work has been reported in the literature both in the area of fundamental applications of reliability concepts as well as in the applied field [13-15]. The reader is advised to refer to the references for a summary of the extensive literature review conducted.

RANDOM VARIABLE IDENTIFICATION

The discussion of the methodology used for the probabilistic analysis is provided in the next section. First, the random variables in the problem are identified. They are: Maximum Time of Operation (MTO) and Operation Time of each Unit (OTU). The collected data for MTO (in hours) is given in Table 1. There are four units associated with each of two Normal Operational Periods (NOP), two units were supposed to have failed to operate during normal use in two different systems (defined herein as Operation 1 and Operation 2). The six other unfailed units are available for study. Hence, OTU data for all the above mentioned units (failed as well as unfailed units) is collected from history documentation prepared by Mikula [16]. Probabilistic analysis is done in this study for two kinds of data. One set of data is classified a "SPECIFIC DATA" which deals with OTU associated with the six unfailed units. This data is shown in Table 2. The other kind of data is classified as "ALL DATA" in which the OTU of all units is collected. This data is shown in Table 3. For the failed units the OTU data is classified under three categories, namely, Perfect System (PS), Imperfect System 1 (IPS-1), and Imperfect System 2 (IPS-2). Before discussing the data set for each of these systems for probabilistic analysis, some explanation regarding two of the failed units is necessary.

Both were used successfully for some period of time. Hence, the data for these units constitutes a mixture of the OTU of these units in operations where the OTU is assumed as equal to MTO of that NOP (the no failure times), along with OTU of these units in periods where they are supposed to have failed. It is in the later part that a distinction is made between the three types of systems.

The following discussion relates to units 1 through 4 (Table 2) associated with Operation 1. For a perfect System the total data for probabilistic analysis consists of the OTU for unfailed units 1, 2, and 3 (assumed as equal to MTO of Operation 1) and the OTU for the failed unit 4. As previously indicated, this includes data for the unfailed unit 4 for other operations along with data for failed unit 4 corresponding to Operation 1 (assumed also equal to the corresponding MTO). For an Imperfect System 1 (IPS-1), the total data for probabilistic analysis consists of the OTU for unfailed units 1, 2, and 3 (again assumed as equal to the MTO of Operation 1) and the OTU for failed unit 4. The latter part includes the data for unfailed unit 4 along with data for failed unit 4 corresponding to the operation in consideration which is assumed as 1% of the corresponding MTO. For an Imperfect System 2 (IPS-2), the total data for probabilistic analysis consists of the OTU for unfailed units 1, 2, and 3 (again assumed as equal to the MTO of Operation 1) and the OTU of failed unit 4. The latter part includes the data for unfailed unit 4 along with the data for failed unit 4 corresponding to the special operation in consideration which is assumed as zero and the simulated OTU values for unit 4. It is to be noted that no data exists regarding the OTU values of the failed unit 4 after its use. So, for this analysis it is assumed that the simulated OUT values for unit 4 after its failure are 10% of the corresponding OUT values before its failure. The same discussion regarding Perfect System, Imperfect System 1 and Imperfect System 2 also applies to OTU values of unfailed units 5, 6, and 7 and failed unit 8 associated with another operation (Operation 2). The MTO values dealing with case of "SPECIFIC DATA" associated with Operations 1 and 2 are tabulated in Tables 4 and 5, respectively. These will be used in conjunction with Table 2 data of OTU values while the MTO values tabulated in Table 1 for case of "ALL DATA" will be used in conjunction with Table 3 data of OTU values.

METHODOLOGY

The basic methodology used for probabilistic analysis is that of Monte Carlo simulation. This method is well discussed in the literature [17, 18]. As is pointed out in the previous section, the random variables relate to OTU of various units and MTO. Two kinds of distributions are assumed for random variables - normal and uniform. Two kinds of failures are discussed - component failure and system failure. Both of these failures are discussed below.

Component Failure

The basic equation is given below:

$$P_F = P\ (OTU < MTO) \tag{1}$$

Where, P (--) = probability of the event under consideration

OTU = operation time of unit under consideration

MTO = maximum time of operation

Monte Carlo simulation is used for evaluation of failure probabilities. Units 4 and 8 are considered for evaluation of component failure as these are supposed to have failed during Operation 1 and Operation 2, respectively. The data for "SPECIFIC DATA" (Tables 2, 4, and 5) and "ALL DATA" (Tables 1 and 3) are used for evaluation of probability of failure values for
units 4 and 8. All three systems — Perfect System, Imperfect System 1 and Imperfect System 2 — data are used for evaluation of P_F values as discussed in the previous section.

System Failure

The failure of any unit (defined by Equation (1)) is assumed to result in a potential loss of system. Since a system consists of four units, this would imply that the failure of any unit results in the failure of the system itself for single unit failure or when there is no redundancy in the system. Expressing mathematically [17, 18],

$$\begin{aligned}(P_F)_{\text{Operation 1}} = P\ [&\{(OTU)/1<MTO\} \cup \{(OTU)/4<MTO\}\\ &\cup \{(OTU)/2<MTO\} \cup \{(OTU)/3<MTO\}]\end{aligned} \qquad (2)$$

$$\begin{aligned}(P_F)_{\text{Operation 2}} = P\ [&\{(OTU)/5<MTO\} \cup \{(OTU)/6<MTO\}\\ &\cup \{(OTU)/8<MTO\} \cup \{(OTU)/7<MTO\}]\end{aligned} \qquad (3)$$

For a dual unit failure (assuming redundancy in the system) the mathematical relation for probability of failure of the system can be expressed as:

$$\begin{aligned}(P_F)_{\text{Operation 1}} = P\ [&\{(OTU)_1<MTO\}\ \{(OTU)_2<MTO\}\\ &\cup \{(OTU)_1<MTO\}\ \{(OTU)_3<MTO\}\\ &\cup \{(OTU)_1<MTO\}\ \{(OTU)_4<MTO\}\\ &\cup \{(OTU)_2<MTO\}\ \{(OTU)_3<MTO\}\\ &\cup \{(OTU)_2<MTO\}\ \{(OTU)_4<MTO\}\\ &\cup \{(OTU)_3<MTO\}\ \{(OTU)_4<MTO\}]\end{aligned} \qquad (4)$$

$$\begin{aligned}(P_F)_{\text{Operation 2}} = P\ [&\{(OTU)_5<MTO\}\ \{(OTU)_6<MTO\}\\ &\cup \{(OTU)_5<MTO\}\ \{(OTU)_7<MTO\}\end{aligned}$$

$$U\ \{(OTU)_5 < MTO\}\ \{(OTU)_8 < MTO\}$$

$$U\ \{(OTU)_6 < MTO\}\ \{(OTU)_7 < MTO\}$$

$$U\ \{(OTU)_6<MTO\}\ \{(OTU)_8<MTO\}$$

$$U\ \{(OTU)_7<MTO\}\ \{(OTU)_8<MTO\}] \qquad (5)$$

Monte Carlo simulation is used to calculate the probability of failure of Operation 1 and Operation 2 using the pertinent random values of OTU of various units. As can be seen from Equation (2) and (4), the calculation of $(P_F)_{\text{Operation 1}}$ incorporates the OTU values of 1, 2, 3, and 4. Similarly, it can be seen from Equations (3) and (5) the calculation of $(P_F)_{\text{Operation 2}}$ incorporates the OTU values of 5, 6, 7, and 8. Again, as in the case of component failures, the P_F of the system is calculated using the data for "SPECIFIC DATA" and "ALL DATA".

RESULTS AND DISCUSSION

Single Unit Failure

The results of reliability analysis with the assumptions of normal distribution for various random variables are tabulated in Table 6 for single unit failure. Table 7 shows similar results with the assumption of uniform distribution for random variables. As can be seen from the results, the predicted change in P_F for the previously failed units is as high as 49% above the base line (Perfect System) for the worst case, with the assumption that the random variables follow either normal or uniform distribution. Regarding the percent change in system probability of failure, it was found that the maximum value is as high as 36% measured with respect to Perfect System as base from the results of both normal and uniform distribution.

Dual Unit Failure

The results of reliability analysis for dual unit failure are tabulated in Tables 8 and 9 with the assumption of normal distribution and uniform distribution, respectively. The predicted change in P_F for the previously failed units is at the same level as single unit failure for both types of distribution. As expected, the change in system P_F has reduced considerably (with highest value of 16%) due to consideration of dual unit failure.

CONCLUSIONS

A methodology has been developed in this paper for evaluating the probability of failures of previously failed units as well as the system itself, which uses these units. It has been found that the probability of failures increases significantly if failed units are returned to stock for use in future operations of the system without corrective action. Hence, units require corrective action to correct these types of failures before reusing them in the system.

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TABLE 1 MAXIMUM TIME OF OPERATION (MTO) OF VARIOUS OPERATIONS

Sequence #	MTO (Hours)	Sequence #	MTO (Hours)
1	146	38	193
2	145	39	214
3	191	40	213
4	168	41	331
5	145	42	191
6	197	43	191
7	192	44	237
8	74	45	175
9	168	46	144
10	168	47	222
11	170	48	240
12	191	49	240
13	170	50	236
14	98	51	336
15	169	52	260
16	165	53	199
17	146	54	335
18	0	55	270
19	97	56	354
20	105	57	263
21	120	58	270
22	97	59	263
23	121	60	98
24	120	61	399
25	120	62	235
26	261	63	214
27	106	64	260
28	121	65	382
29	98	66	197
30	118	67	214
31	215	68	378
32	144	69	221
33	199	70	241
34	218	71	406
35	213	72	243
36	128	73	424
37	167		

TABLE 2 OPERATION TIME (IN HOURS) OF UNITS (OTU) FOR UNITS 1 THROUGH 8

("Specific Data" – Includes Data for Operations 1 and 2 Only)

Units Associated with Operation 1						Units Associated with Operation 2					
Unit 1	**Unit 4**			**Unit 2**	**Unit 3**	**Unit 5**	**Unit 6**	**Unit 8**			**Unit 7**
	PS	**IPS-1**	**IPS-2**					**PS**	**IPS-1**	**IPS-2**	
263	263	263	263	98	263	146	382	146	146	146	382
235	235	235	235	165	235	382	378	382	3.82	0	378
197	197	1.97	0	263	197	378	406			14.6	406
221			26.3	235	221	406	424				424
243			23.5	197	243	424					
				221							
				243							

TABLE 3 OPERATION TIME (IN HOURS) OF UNITS (OTU) FOR UNITS 1 THROUGH 8

("All Data" – Includes Data for All Operations)

Units Associated with Operation 1							Units Associated with Operation 2					
Unit 1	Unit 4			Unit 2	Unit 3		Unit 5	Unit 6	Unit 8			Unit 7
	PS	IPS-1	IPS-2						PS	IPS-1	IPS-2	
263	213	213	213	98	213		146	97	146	146	146	145
235	191	191	191	165	191		382	120	97	97	97	192
197	144	144	144	263	144		378	120	120	120	120	74
221	240	240	240	235	240		406	121	106	106	106	168
243	263	263	263	197	263		424	98	118	118	118	170
	235	235	235	221	235			199	144	144	144	170
	197	1.97	0		197			128	213	213	213	105
			21.3		221			193	167	167	167	97
			19.1		243			175	214	214	214	120
			14.4					222	191	191	191	106
			24.0					260	382	3.82	0	118
			26.3					270			14.6	144
			23.5					382			9.7	213
								378			12.0	167
								406			10.6	214
								424			11.8	191
											14.4	382
											21.3	378
											16.7	406
											21.4	424
											19.1	

TABLE 4 MAXIMUM TIME OF OPERATION (MTO) (OPERATION 1 - "SPECIFIC DATA")					
Sequence #	**MTO (Hours)**		**Sequence #**	**MTO (Hours)**
14	98		37	167
16	165		39	214
20	105		42	191
22	97		59	263
24	120		62	235
27	106		66	197
30	118		69	221
32	144		72	243
35	213			

TABLE 5 MAXIMUM TIME OF OPERATION (MTO) (OPERATION 2 – "SPECIFIC DATA")				
Sequence #	MTO (Hours)		Sequence #	MTO (Hours)
17	146		51	336
23	121		54	335
26	261		56	354
31	215		65	382
34	218		68	378
41	331		71	406
44	237		73	424
48	240			

TABLE 6 PROBABILITY OF FAILURES FOR VARIOUS SYSTEMS (NORMAL DISTRIBUTION)							
Single Unit Failure							
		Base Value P_F of Unit	Change in P_F from Base Value P_F of Unit		Base Value P_F of System	Change in System* P_F from Base Value P_F of System	
Unit No.	Data Used For Operation	Perfect System	Imperfect System 1	Imperfect System 2	Perfect System	Imperfect System 1	Imperfect System 2
4	Operation 1	17.4%	34.0%	49.0%	41.4%	25.0%	34.0%
4	ALL	46.9%	10.0%	29.0%	64.4%	9.0%	18.0%
8	Operation 2	56.7%	37.0%	41.0%	68.8%	26.0%	29.0%
8	ALL	61.8%	13.0%	25.0%	81.1%	4.0%	11.0%

*System for Unit 4 Includes Units 1 through 4 for Operation 1
System for Unit 8 Includes Units 5 through 8 for Operation 2

TABLE 7 PROBABILITY OF FAILURES FOR VARIOUS SYSTEMS (UNIFORM DISTRIBUTION)							
Single Unit Failure							
		Base Value P_F of Unit	Change in P_F from Base Value P_F of Unit		Base Value P_F of System	Change in System* P_F from Base Value P_F of System	
Unit No.	Data Used For Operation	Perfect System	Imperfect System 1	Imperfect System 2	Perfect System	Imperfect System 1	Imperfect System 2
4	Operation 1	19.5%	48.0%	49.0%	53.2%	26.0%	26.0%
4	ALL	62.5%	17.0%	17.0%	75.2%	11.0%	11.0%
8	Operation 2	52.6%	47.0%	47.0%	63.6%	36.0%	36.0%
8	ALL	52.6%	34.0%	34.0%	73.9%	15.0%	16.0%

*System for Unit 4 Includes Units 1 through 4 for Operation 1
System for Unit 8 Includes Units 5 through 8 for Operation 2

TABLE 8 PROBABILITY OF FAILURES FOR VARIOUS SYSTEMS (NORMAL DISTRIBUTION)							
Dual Unit Failure							
		Base Value P_F of Unit	Change in P_F from Base Value P_F of Unit		Base Value P_F of System	Change in System* P_F from Base Value P_F of System	
Unit No.	Data Used For Operation	Perfect System	Imperfect System 1	Imperfect System 2	Perfect System	Imperfect System 1	Imperfect System 2
4	Operation 1	17.4%	34.0%	49.0%	20.4%	8.0%	12.0%
4	ALL	46.9%	10.0%	29.0%	48.8%	3.0%	8.0%
8	Operation 2	56.7%	37.0%	41.0%	29.5%	9.0%	10.0%
8	ALL	61.8%	13.0%	25.0%	55.3%	5.0%	9.0%

*System for Unit 4 Includes Units 1 through 4 for Operation 1
System for Unit 8 Includes Units 5 through 8 for Operation 2

TABLE 9 PROBABILITY OF FAILURES FOR VARIOUS SYSTEMS (UNIFORM DISTRIBUTION)							
Dual Unit Failure							
		Base Value P_F of Unit	Change in P_F from Base Value P_F of Unit		Base Value P_F of System	Change in System* P_F from Base Value P_F of System	
Unit No.	Data Used For Operation	Perfect System	Imperfect System 1	Imperfect System 2	Perfect System	Imperfect System 1	Imperfect System 2
4	Operation 1	19.5%	48.0%	49.0%	26.5%	16.0%	16.0%
4	ALL	62.5%	17.0%	17.0%	64.7%	4.0%	4.0%
8	Operation 2	52.6%	47.0%	47.0%	35.8%	11.0%	11.0%
8	ALL	52.6%	34.0%	34.0%	55.1%	10.0%	10.0%

*System for Unit 4 Includes Units 1 through 4 for Operation 1
System for Unit 8 Includes Units 5 through 8 for Operation 2