Space Transportation System Availability Requirement and Its Influencing Attributes Relationships

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It is important that engineering and management accept the need for an availability requirement that is derived with its influencing attributes. It is the intent of this paper to provide the visibility of relationships of these major attribute drivers (variables) to each other and the resultant system inherent availability. Also important to provide bounds of the variables providing engineering the insight required to control the system's engineering solution, e.g., these influencing attributes become design requirements also. These variables will drive the need to provide integration of similar discipline functions or technology selection to allow control of the total parts count. The relationship of selecting a reliability requirement will place a constraint on parts count to achieve a given availability requirement or if allowed to increase the parts count will drive the system reliability requirement higher. They also provide the understanding for the relationship of mean repair time (or mean down time) to maintainability, e.g., accessibility for repair, and both the mean time between failure, e.g., reliability of hardware and availability. The concerns and importance of achieving a strong availability requirement is driven by the need for affordability, the choice of using the two launch solution for the single space application, or the need to control the spare parts count needed to support the long stay in either orbit or on the surface of the moon. Understanding the requirements before starting the architectural design concept will avoid considerable time and money required to iterate the design to meet the redesign and assessment process required to achieve the results required of the customer's space transportation system. In fact the impact to the schedule to being able to deliver the system that meets the customer's needs, goals, and objectives may cause the customer to compromise his desired operational goal and objectives resulting in considerable increased life cycle cost of the fielded space transportation system.

Nomenclature

A_i	=	inherent availability
A_a	=	achieved availability
A_o	=	operational availability
MTBF	=	mean time between failure
MTTR	=	mean time to repair
λ	=	failure rate or the reciprocal of the MTBF
r	=	number of failures or repairs
N	=	total parts count
t	=	system exposure time
Pr	=	probability

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I. Introduction

IT is essential that management and engineering understand the need for a derived availability requirement for the customer's space transportation system. It is also essential to provide engineering and management the visibility of the several variables that determine availability required to enable a system's key goals and objectives. This relationship of the variables driving the availability-capability needs must be understood by all decision makers involved. This paper will address the inherent availability which only addresses the mean downtime as that mean time to repair or the time to determine the failed article, remove it, install a replacement article, and verify the functionality of the repaired system. Also with inherent availability the mean uptime will only consider the mean time between failures (for example, another form of availability addresses mean time between maintenance that includes both preventive and corrective maintenance) that require the repair of the system to be functional. It is also essential that management and engineering understand all influencing attribute relationships to each other and to the resultant inherent-availability requirement. Fig.1 illustrates the influences these attribute relationships to each other and to the resultant availability requirement. This visibility will provide the decision makers with the understanding necessary to place constraints on the design definition for the major drivers that will determine the inherent availability, safety, reliability, maintainability, and the life cycle cost of the fielded system provided to the customer. This inherent availability requirement may be driven by the need to use a multiple launch approach to placing humans on the moon or the desire to control the number of spare parts required to support long stays in either orbit or on the surface of the moon or mars.

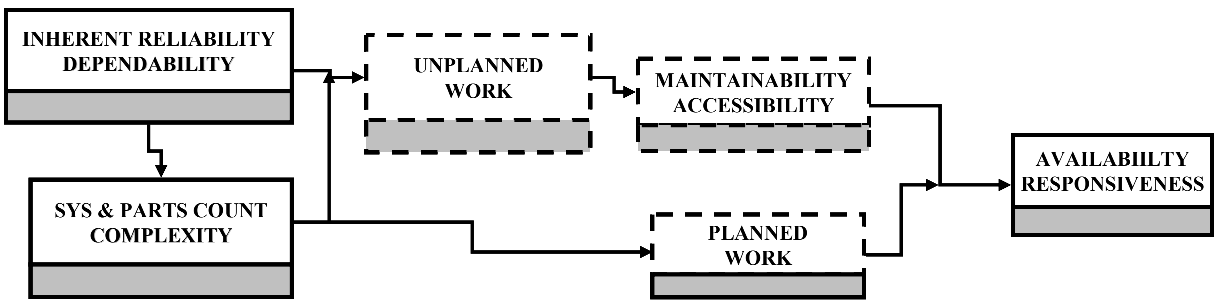

Figure 1. Availability influence diagram

II. Background

Availability is the probability that a repairable system is operational—thus, availability is a function of both reliability and maintainability. Reliability is the probability a system will perform its intended function without failure for a specified period of time under specified conditions. Maintainability is the probability of restoring or repairing a system within a period of time when maintenance is performed in accordance with prescribed procedures.

Availability and not reliability addresses downtime (i.e., time for maintenance, repair, and replacement activities). As with reliability, availability can be either a demonstrated or predictive measure of performance. Demonstrated availability is simply (uptime) / (uptime + downtime). Predictive availability has three types, namely, at time t (point availability), over an interval from t_1 to t_2 (interval availability), or over the long run as $t \rightarrow \infty$ (steady-state availability).

Steady-state availability has three common forms (with each depending on the definitions of uptime and downtime), namely, inherent availability (Ai), achieved availability (Aa), and operational availability (Ao). Inherent availability is based solely on the failure (reliability) distribution and the downtime (maintainability) distribution and is an important system parameter for concept-architectural-design definition through systems-trade studies.

The maintainability parameter of inherent availability only accounts for the time to diagnose and locate the failed article, access and repair it, and verify the functionality of the repaired system. The maintainability parameter for achieved availability is the same as inherent availability except it includes the time for preventive maintenance. Last, the maintainability parameter for operational availability is the same as achieved availability except it includes the time for logistics and administrative delays.

For the purpose of this paper we will only discuss inherent availability (A_i) as shown in Eq. 1,

$$A_i = MTBF / (MTBF + MTTR) \quad (1)$$

where MTBF is the mean time between failure and MTTR is the mean time to repair. That is, MTBF is the average time between system failures (i.e., the average time the system performs its intended function), and MTTR is the average down time (i.e., the time to identify and access the failed article, repair or replace the article, and verify the functionality of the repaired system). Stating an availability requirement by itself will not accomplish the requirement's intent. Why, because there are three major drivers that influence and enable the achievement of the availability requirement. These drivers are reliability, maintainability, and total parts count (formerly referred to as "system element count"). The availability requirement and the mentioned drivers must be developed and linked together to form interdependent requirements. The relationship of these drivers and the desired level of inherent availability must be understood by both engineering and management to systematically achieve the customer's needs and goals.

III. Understanding the Availability and its Drivers

A. Inherent Availability and its Influencing Attributes

We will address inherent availability from a design perspective. By emphasizing the importance of the key attributes that influence availability, we can control the need to perform unplanned work during long space missions or during the critical phases of the launch operation. Since inherent availability is a mathematical function of MTBF and MTTR, availability is determined by both parameters (drivers) and not one. Thus, reliability and its common metric (MTBF) do not equate to availability. As MTBF increases, upper-bound MTTR increases for lower-bound availability requirement. Therefore, if the mission cannot accommodate the amount of down time from the predicted MTTR requirement, there is a need for selecting a higher availability requirement. If the opposite approach is taken to reduce MTBF in order to reduce the allowable MTTR, the probability of the number of failures would increase resulting in more replacement parts and the same total down time. However, the impact to the mission will be much greater. That is, there would be a greater burden on logistics and higher life cycle cost due to the increased demand in providing more parts. Table 1 below illustrates this relationship between the requirements for MTTR and MTBF for different availability requirements. This table assumes there is one system element with a mission time of one unit (hours will be used in this paper) and with failures occurring at a constant rate.

Table 1. Availability requirement as a function of the reliability requirement and maintainability requirement for a fixed mission time

	Availability (A)						
System Reliability	90%	94%	98%	99%	99.50%	99.90%	MTBF = -1/ln R
0.9500	2.17	1.24	0.40	0.20	0.10	0.02	19.496
0.9800	5.50	3.16	1.01	0.50	0.25	0.05	49.498
0.9900	11.06	6.35	2.03	1.01	0.50	0.10	99.499
0.9940	18.46	10.61	3.39	1.68	0.84	0.17	166.166
0.9950	22.17	12.73	4.07	2.02	1.00	0.20	199.500
0.9960	27.72	15.93	5.09	2.52	1.25	0.25	249.500
0.9980	55.50	31.88	10.19	5.05	2.51	0.50	499.500
0.9990	111.06	63.80	20.40	10.10	5.02	1.00	999.500
0.9998	555.50	319.12	102.03	50.50	25.12	5.00	4999.500
0.9999	1,111.06	638.27	204.07	101.01	50.25	10.01	9999.500
	MTTR (Hours)						

To understand the relationship between increased hardware failures and reduced reliability, we will examine the probability of failure, total parts count, and system reliability. The Poisson distribution can be used to predict the exact number of repair or failure events (r) in time period (t) of interest. However, it assumes each part has a constant repair or failure rate λ (where λ is the reciprocal of MTBF) and is immediately repaired or replaced. When the forecast is to determine the likelihood of r or less number of failures, the cumulative Poisson distribution can be used to determine this probability (Pr) and is described in Eq 2

$$\Pr = \sum_{n=0}^{r}\left[e^{-N\lambda t}\left(N\lambda t\right)^{n}/\left(n!\right)\right] \tag{2}$$

where r is the upper bound for the number of failures, N is the total parts count under consideration, λ is the failure rate, and t is time period of interest. Using Eq. 2 and Table 2 illustrate the relationship between system complexity (parts count) and system reliability where Table 2 provides the visibility for the predicted probability of success of controlling the part failures during the period of time of interest. This methodology can be used during design for controlling predicted hardware failures. This methodology places a bound on parts count to system reliability being selected.

Table 2. System Complexity (parts count) shown as a function system reliability and probability of 1 or less failures (events) per one hour time period (mission)

IF: Proposed System Has Serial Element Count (**N**) = **2,000**

Mission Time (**t**) = **1**

Mission's Maximum Failure Count (**r**) = **1**

And:	**Then:**		**Probability Of Success: Failure Count Is r Or Less During t For Various System Complexity Levels (N_{ref}) Based On λ_i**						
System Reliability (R)	**System MTBF**	**Element Failure Rate (λi)**	**1,000**	**1,500**	**2,000**	**2,500**	**5,000**	**10,000**	**20,000**
0.940	16.2	3.0938E-05	0.99953	0.99896	0.99816	0.99716	0.98920	0.96096	0.87189
0.945	17.7	2.8285E-05	0.99961	0.99913	0.99846	0.99761	0.99089	0.96680	0.88926
0.950	19.5	2.5647E-05	0.99968	0.99928	0.99873	0.99803	0.99245	0.97223	0.90585
0.955	21.7	2.3022E-05	0.99974	0.99942	0.99897	0.99841	0.99386	0.97724	0.92155
0.960	24.5	2.0411E-05	0.99979	0.99954	0.99919	0.99874	0.99513	0.98180	0.93623
0.965	28.1	1.7814E-05	0.99984	0.99965	0.99938	0.99904	0.99626	0.98590	0.94977
0.970	32.8	1.5230E-05	0.99989	0.99974	0.99955	0.99929	0.99724	0.98952	0.96204
0.975	39.5	1.2659E-05	0.99992	0.99982	0.99968	0.99951	0.99808	0.99263	0.97288
0.980	49.5	1.0101E-05	0.99995	0.99989	0.99980	0.99969	0.99877	0.99523	0.98214
0.985	66.2	7.5568E-06	0.99997	0.99994	0.99989	0.99982	0.99930	0.99728	0.98967
0.990	99.5	5.0252E-06	0.99999	0.99997	0.99995	0.99992	0.99969	0.99878	0.99528

When evaluating total parts count, this can be considered in two different ways. If the concern is for affordability, the total parts count considers all components that could be considered to have a failure mode. Any part failure will result in added maintenance burden and result in added life cycle cost. However, if the concern is for achieving a successful launch on time or for the in-space application for long term space flight, only the critical components (parts) should be considered that would impact the successful mission accomplishment. Because of this difference in objectives, the designer will probably want to perform both evaluations to allow the achievement of both objectives which can be controlled and accomplished by the design process. These attribute relationships and availability can be made more visible by examining scenario examples.

B. An example of Space Transportation Application

Let's work an example case through this process to allow better visibility of using these aids. Let's assume for a repairable system the requirements are a 45-day period (1080 hours) with 0.98 system reliability, 98% system availability, and upper-bound MTTR at 216 hours. This 45-day target may represent a desired total time for receiving the hardware at the launch site, integrating the major elements, servicing the consumables, installing and connecting any ordinance, and launching the space transportation system into space (including approximately 20% for hardware replacement, e.g., MTTR). We can see from Table 3 that the upper bound MTTR for our example is 1090.98 hours. However, we must either select a higher availability or lower system reliability since the calculated upper-bound MTTR greatly exceeds the 216-hour requirement. Again using Table 3 when we do not change the 0.98 system reliability requirement, the availability requirement needs to be adjusted upwards to be ~ 99.9%

providing an upper-bound MTTR of 53.51 hours. The other option would be to reduce system reliability to 0.90 to retain the upper-bound MTTR requirement of 216 hours. However, when we select a lower reliability, we need to address the likelihood (probability) of experiencing additional hardware failures. It can be seen from Table 4 that the system complexity requirement would be constrained to ~ 10,765 critical parts count maximum at a 98% or better probability of success while predicting the failures to be 2 or less parts per event. However, the upper-bound MTTR for these 2 parts will only be ~ 209 hours to achieve the availability of 98%. This option can be compared to the reliability choice of 0.98 where the critical parts constraint would be ~ 56,125 vs. the 10,765 with the reliability reduction to 0.90.

Table 3. Availability shown highlighted as a function of system reliability and mean time to repair in hours

Availability (A) = Mean Time Between Failure (MTBF) / (MTBF + Mean Time To Repair (MTTR))

A = MTBF / (MTBF+MTTR) or MTTR = MTBF(1-A / A) t = 1080 Hours

A family of curves can be created for A = 90% to 99.9% with Sys. Reliability (R) = 0.95 to 0.99996
Then MTTR is calculated for @ each A value

System Reliability	Availability (A) 90%	98%	99%	99.50%	99.90%	99.98%	99.996%	MTBF = -t/ln R
0.9000	1,138.95	209.19	103.54	51.51	10.26	2.05	0.410	10250.52
0.9800	5,939.80	1,090.98	539.98	268.63	53.51	10.69	2.138	53458.18
0.9900	11,939.90	2,193.04	1,085.45	540.00	107.57	21.50	4.299	107459.10
0.9940	19,939.94	3,662.44	1,812.72	901.81	179.64	35.90	7.179	179459.46
0.9950	23,939.95	4,397.13	2,176.36	1,082.71	215.68	43.10	8.619	215459.55
0.9960	29,939.96	5,499.18	2,721.81	1,354.07	269.73	53.90	10.779	269459.64
0.9980	59,939.98	11,009.38	5,449.09	2,710.85	540.00	107.91	21.579	539459.82
0.9990	119,939.99	22,029.79	10,903.64	5,424.42	1,080.54	215.94	43.180	1079459.91
0.9995	239,939.99	44,070.61	21,812.73	10,851.56	2,161.62	431.98	86.382	2159459.95
0.9998	599,940.00	110,193.06	54,540.00	27,132.96	5,404.86	1,080.11	215.987	5399459.98
0.9999	1,199,940.00	220,397.14	109,085.45	54,268.64	10,810.27	2,160.32	431.996	10799459.99

MTTR (Hours)

Again it can be seen from Table 4 that it may be desirable to increase system reliability if it is unreasonable to constrain the parts count below ~56,125 with a probability of success greater than ~ 98%. If we select system reliability greater than 0.98 to accommodate an increased parts count constraint, we will again need to reassess the availability requirement value for 99.9% to retain the MTTR requirement to ~ 216 hours. Attention should be paid to the element (part) failure rate requirement to attain these system reliability values to assure they are obtainable.

Table 4. System Complexity (parts count) constraint example shown as a function of system reliability (0.90 & 0.98) and 98% probability of success of controlling failures to 2 or less / event

IF: Proposed System Has Serial Element Count (**N**) = **2,000**

Mission Time (**t**) = **1,080**

Mission's Maximum Failure Count (**r**) = **2**

And:	**Then:**		**Probability Of Success: Failure Count Is r Or Less During t For Various System Complexity Levels (N_{ref}) Based On λ_i**						
System Reliability (R)	**System MTBF**	**Element Failure Rate (λi)**	**1,000**	**1,500**	**2,000**	**2,500**	**5,000**	**10,765**	**56,125**
0.900	10,250.5	4.8778E-08	0.99998	0.99992	0.99982	0.99965	0.99750	0.98001	0.43297
0.945	19,091.3	2.6190E-08	1.00000	0.99999	0.99997	0.99994	0.99958	0.99625	0.78658
0.950	21,055.4	2.3747E-08	1.00000	0.99999	0.99998	0.99996	0.99968	0.99714	0.82389
0.955	23,455.9	2.1317E-08	1.00000	0.99999	0.99998	0.99997	0.99977	0.99789	0.85893
0.960	26,456.3	1.8899E-08	1.00000	1.00000	0.99999	0.99998	0.99984	0.99850	0.89107
0.965	30,313.9	1.6494E-08	1.00000	1.00000	0.99999	0.99999	0.99989	0.99898	0.91974
0.970	35,457.3	1.4101E-08	1.00000	1.00000	1.00000	0.99999	0.99993	0.99935	0.94438
0.975	42,657.7	1.1721E-08	1.00000	1.00000	1.00000	0.99999	0.99996	0.99962	0.96457
0.980	53,458.2	9.3531E-09	1.00000	1.00000	1.00000	1.00000	0.99998	0.99980	0.98002
0.985	71,458.6	6.9971E-09	1.00000	1.00000	1.00000	1.00000	0.99999	0.99992	0.99072
0.990	107,459.1	4.6529E-09	1.00000	1.00000	1.00000	1.00000	1.00000	0.99997	0.99697

For the purposes of determining the availability of the system during a more critical time during the launch operation, we provide an assessment of the last 16 hours (two work shifts) of the total 45-day flow time by adjusting the value for t in our model to 16 hours. For this evaluation, select a system reliability of 0.98 and the availability of 0.98% with an upper-bound MTTR value of 5 hour for hardware replacement. It can be seen from Table 6 that a reliability value of 0.98 must be selected to achieve a one or less failure prediction within the 16 hours while constraining the critical parts count to 21,250 with minimum of a 0.98% probability of success. From Table 5 it can be determined with a system reliability value of 0.98 (MTBF of ~ 792 hours) that the availability must be 99.5% to constrain the MTTR to within the desired 5 hours. The first selected availability value of 0.98% would have allowed the MTTR of ~ 16 hours which is not compatible with our requirement. If it is desirable to increase the critical parts constraint above the 21,250, the system reliability requirement may need to be raised to 0.99 at an availability requirement of 99.9% to allow constraining the parts failure potential to one element (part) during this final 16 hour with a maximum of ~ 5 hours for this repair.

Table 5. Availability shown highlighted as a function of system reliability and mean time to repair in hours

Availability (A) = Mean Time Between Failure (MTBF) / (MTBF + Mean Time To Repair (MTTR))

A = MTBF / (MTBF+MTTR) or MTTR = MTBF(1-A / A) t = 16 Hours

A family of curves can be created for A = 90% to 99.9% with Sys. Reliability (R) = 0.95 to 0.99996
Then MTTR is calculated for @ each A value

System Reliability	Availability (A) 90%	98%	99%	99.50%	99.90%	99.97%	99.994%	MTBF = -t/ln R
0.9500	34.66	6.37	3.15	1.57	0.31	0.09	0.02	311.93
0.9800	88.00	**16.16**	8.00	**3.98**	0.79	0.24	0.05	**791.97**
0.9900	176.89	32.49	16.08	8.00	1.59	0.48	0.10	1591.99
0.9940	295.41	54.26	26.86	13.36	2.66	0.80	0.16	2658.66
0.9950	354.67	65.14	32.24	16.04	3.20	0.96	0.19	3191.99
0.9960	443.55	81.47	40.32	20.06	4.00	1.20	0.24	3991.99
0.9980	888.00	163.10	80.73	40.16	8.00	2.40	0.48	7992.00
0.9990	1,776.89	326.37	161.54	80.36	16.01	4.80	0.96	15992.00
0.9998	8,888.00	1,632.49	808.00	401.97	80.07	24.00	4.80	79992.00
0.99990	17,776.89	3,265.14	1,616.08	803.98	160.15	48.01	9.60	159992.00

MTTR (Hours)

We have discovered from Tables 4 and 6 these element-failure rates may not be achievable; therefore, we will address this subject from another perspective. Using Table 7 we will assume a 2000-serial-element count for this example and select a reasonable element-failure rate to determine the System MTBF and our probability for success of achieving 98% or better for this 16 hour mission when allowing 1 or less failures to occur. From Table 7 it is determined that an availability value of 99% can be selected when considering the element-failure rate of 1.5E-06 while accommodating the 5 hour MTTR requirement. However, from Table 6 we see that the maximum parts count is lowered to between 5,000-10,000 elements.

Table 6. System Complexity (parts count) example shown as a function of system reliability (0.98) and 98% probability of success of controlling failures to 1 or less per event in time (16 hours)

IF: Proposed System Has Serial Element Count (**N**) = **2,000**

Mission Time (**t**) = **16**

Mission's Maximum Failure Count (**r**) = **1**

And:	**Then:**		**Probability Of Success: Failure Count Is r Or Less During t For Various System Complexity Levels (N_{ref}) Based On λ_i**						
System Reliability (R)	**System MTBF**	**Element Failure Rate (λi)**	**1,000**	**1,500**	**2,000**	**2,500**	**5,000**	**10,000**	**21,250**
0.940	258.6	1.9336E-06	0.99953	0.99896	0.99816	0.99716	0.98920	0.96096	0.85885
0.945	282.8	1.7678E-06	0.99961	0.99913	0.99846	0.99761	0.99089	0.96680	0.87775
0.950	311.9	1.6029E-06	0.99968	0.99928	0.99873	0.99803	0.99245	0.97223	0.89586
0.955	347.5	1.4389E-06	0.99974	0.99942	0.99897	0.99841	0.99386	0.97724	0.91305
0.960	391.9	1.2757E-06	0.99979	0.99954	0.99919	0.99874	0.99513	0.98180	0.92918
0.965	449.1	1.1133E-06	0.99984	0.99965	0.99938	0.99904	0.99626	0.98590	0.94411
0.970	525.3	9.5185E-07	0.99989	0.99974	0.99955	0.99929	0.99724	0.98952	0.95767
0.975	632.0	7.9118E-07	0.99992	0.99982	0.99968	0.99951	0.99808	0.99263	0.96970
0.980	792.0	6.3133E-07	0.99995	0.99989	0.99980	0.99969	0.99877	0.99523	0.98001
0.985	1,058.6	4.7230E-07	0.99997	0.99994	0.99989	0.99982	0.99930	0.99728	0.98841
0.990	1,592.0	3.1407E-07	0.99999	0.99997	0.99995	0.99992	0.99969	0.99878	0.99469

Table 7. Availability shown highlighted as a function of system reliability and mean time to repair in hours

Availability (A) = Mean Time Between Failure (MTBF) / (MTBF + Mean Time To Repair (MTTR))

A = MTBF / (MTBF+MTTR) or MTTR = MTBF(1-A / A)

t = 16 Hours

N = 2,000

A family of curves can be created for A = 99% to 99.999% with Sys. Reliability (R) = 0.90 to 0.99999
Then MTTR is calculated @ each A value

	Availability (A)							
Element Failure Rate (λ_i)	72.00%	98.50%	99.00%	99.50%	99.90%	99.95%	99.99%	**MTBF = 1 / N*λ_i**
1.00E-07	1,944.44	76.14	50.51	25.13	5.01	2.50	0.50	5,000.00
1.00E-06	194.44	7.61	5.05	2.51	0.50	0.25	0.05	500.00
1.50E-06	129.63	5.08	3.37	1.68	0.33	0.17	0.03	333.33
1.00E-05	19.44	0.76	0.51	0.25	0.05	0.03	0.01	50.00
1.50E-05	12.96	0.51	0.34	0.17	0.03	0.02	0.00	33.33
1.00E-04	1.94	0.08	0.05	0.03	0.01	0.00	0.00	5.00
1.50E-04	1.30	0.05	0.03	0.02	0.00	0.00	0.00	3.33
1.00E-03	0.19	0.01	0.01	0.00	0.00	0.00	0.00	0.50
	MTTR (Hours)							

C. An example of long term In-Space Application

Let us now look at an example of long-term exposure in space without the opportunity to provide re-supply of any hardware from earth. This might be considered as a trip to another planet like Mars where trip time may be approximately two years. First, we must develop the reliability and maintainability requirements for this application of ~ 17,600 hour mission. We will choose a desired system reliability of 0.98 with an availability of 99.99%. We can see from Table 8 that our upper-bound MTTR will be ~ 87 hours. However, we can be see from Table 9 that the total parts count must be constrained from 2000 to 4000 (reliability of 0.98 to 0.99) critical parts if we assume there are no failures allowed (Availability of 100%) and at a probability of success of 98% or better. But allowing for our availability goal of 99.99% with 5 or less failures, we can see from Table 10 that our probability of success is ~ 100% based on using parts with an element-failure rate of 5.7394E-10.

Table 8. Availability shown highlighted as a function of system reliability and mean time to repair in hours

Availability (A) = Mean Time Between Failure (MTBF) / (MTBF + Mean Time To Repair (MTTR))

A = MTBF / (MTBF+MTTR) or MTTR = MTBF(1-A / A) t = 17600 Hours

A family of curves can be created for A = 99% to 99.999% with Sys. Reliability (R) = 0.90 to 0.99999
Then MTTR is calculated @ each A value

System Reliability	Availability (A) 99.000%	99.500%	99.900%	99.950%	99.990%	99.995%	99.999%	MTBF = -t/ln R
0.90000	1,687.33	839.42	167.21	83.56	16.71	8.35	1.67	167,045.50
0.95000	3,465.91	1,724.25	343.47	171.65	34.32	17.16	3.43	343,124.77
0.98000	8,799.70	4,377.74	872.04	435.80	87.13	43.56	8.71	871,170.37
0.99000	17,688.74	8,799.93	1,752.94	876.03	175.14	87.56	17.51	1,751,185.26
0.99500	35,466.59	17,644.18	3,514.71	1,756.47	351.15	175.57	35.11	3,511,192.65
0.99990	1,777,688.89	884,377.89	176,167.37	88,039.62	17,600.88	8,800.00	1,759.93	175,991,199.85
0.99995	3,555,466.67	1,768,800.00	352,343.54	176,083.64	35,202.64	17,600.44	3,519.95	351,991,199.93
0.99999	17,777,688.89	8,844,176.88	1,761,752.95	880,435.82	176,016.72	88,003.96	17,600.09	1,759,991,199.99

MTTR (Hours)

Table 9. System Complexity (parts count) example shown as a function of system reliability at (0.98 to 0.99) and 98% probability of success of controlling failures to 0 per event in time; however, the event time is long term in space of 2 years (17,600 hours).

IF: Proposed System Has Serial Element Count (**N**) = **2,000**

Mission Time (**t**) = **17,600**

Mission's Maximum Failure Count (**r**) = **0**

And:	**Then:**		**Probability Of Success: Failure Count Is r Or Less During t For Various System Complexity Levels (N_{ref}) Based On λ_i**						
System Reliability (R)	**System MTBF**	**Element Failure Rate (λi)**	**1,000**	**1,500**	**2,000**	**2,500**	**4,000**	**10,000**	**20,000**
0.940	284,442.6	1.7578E-09	0.96954	0.95465	0.94000	0.92557	0.88360	0.73390	0.53862
0.945	311,117.0	1.6071E-09	0.97211	0.95846	0.94500	0.93173	0.89303	0.75363	0.56796
0.950	343,124.8	1.4572E-09	0.97468	0.96226	0.95000	0.93790	0.90250	0.77378	0.59874
0.955	382,243.6	1.3081E-09	0.97724	0.96606	0.95500	0.94407	0.91203	0.79436	0.63101
0.960	431,140.1	1.1597E-09	0.97980	0.96985	0.96000	0.95025	0.92160	0.81537	0.66483
0.965	494,004.9	1.0121E-09	0.98234	0.97363	0.96500	0.95644	0.93123	0.83683	0.70028
0.970	577,822.0	8.6532E-10	0.98489	0.97741	0.97000	0.96264	0.94090	0.85873	0.73742
0.975	695,162.9	7.1926E-10	0.98742	0.98119	0.97500	0.96885	0.95063	0.88110	0.77633
0.980	871,170.4	5.7394E-10	0.98995	0.98496	0.98000	0.97506	0.96040	0.90392	0.81707
0.985	1,164,511.2	4.2936E-10	0.99247	0.98873	0.98500	0.98129	0.97023	0.92722	0.85973
0.990	1,751,185.3	2.8552E-10	0.99499	0.99249	0.99000	0.98752	0.98010	0.95099	0.90438

Table 10. System Complexity (parts count) example shown as a function of system reliability at 0.98 and ~ 100% probability of success of controlling failures to 5 or less per event in time; however, the event time is long term in space of 2 years (17,600 hours).

IF: Proposed System Has Serial Element Count (**N**) = **2,000**

Mission Time (**t**) = **17,600**

Mission's Maximum Failure Count (**r**) = **5**

And:	**Then:**		**Probability Of Success: Failure Count Is r Or Less During t For Various System Complexity Levels (N_{ref}) Based On λ_i**						
System Reliability (R)	**System MTBF**	**Element Failure Rate (λi)**	**1,000**	**1,500**	**2,000**	**2,500**	**5,000**	**10,000**	**20,000**
0.940	284,442.6	1.7578E-09	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0.99995
0.945	311,117.0	1.6071E-09	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0.99997
0.950	343,124.8	1.4572E-09	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0.99998
0.955	382,243.6	1.3081E-09	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0.99999
0.960	431,140.1	1.1597E-09	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
0.965	494,004.9	1.0121E-09	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
0.970	577,822.0	8.6532E-10	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
0.975	695,162.9	7.1926E-10	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
0.980	871,170.4	5.7394E-10	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
0.985	1,164,511.2	4.2936E-10	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
0.990	1,751,185.3	2.8552E-10	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

We have discovered these element-failure rates are most likely not achievable; therefore, we will address this subject from another perspective. Using Table 11 we will assume a 2000-serial-element count for this example and a list of reasonable element-failure rates to determine the System MTBF and our probability for success of achieving 98% or better for this 17,600 hour (~ 2 years) mission when allowing 100 or less failures to occur. When considering a mission of this type, consideration should be given to accessibility to perform repairs; therefore, we should limit the capability to perform the repair (MTTR) in 2 hours maximum as a design requirement. Using Table 12 we can see that the availability can be lowered to 72% to accommodate this 2 hour each repair) requirement while allowing for repairing up to 100 elements (parts) during the mission.

Table 11. System Complexity (parts count) example shown as a function of element-failure rate (part reliability) at (1.0E-03 to 1.0E-8) and 98% probability of success of controlling failures to 100 or less per event in time; however, the event time is long term in space of 2 years (17,600 hours).

IF: Proposed System Has Serial Element Count (**N**) = **2,000**

Mission Time (**t**) = **17,600**

Mission's Maximum Failure Count (**r**) = **100**

And:	**Then:**		**Probability Of Success: Failure Count Is r Or Less During t For Various System Complexity Levels (N_{ref}) Based On λ_i**						
Element Failure Rate (λi)	**System MTBF**	**System Reliability**	**100**	**300**	**400**	**500**	**2,000**	**3,000**	**4,627**
1.0000E-03	0.5	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
1.5000E-04	3.3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
1.0000E-04	5.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
4.0000E-05	12.5	0.00000	0.99965	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
1.5000E-05	33.3	0.00000	1.00000	0.98968	0.31419	0.00220	0.00000	0.00000	0.00000
1.0000E-05	50.0	0.00000	1.00000	1.00000	0.99965	0.90660	0.00000	0.00000	0.00000
1.5000E-06	333.3	0.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0.98968	0.02242
1.0000E-06	500.0	0.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0.98007
1.5000E-07	3,333.3	0.00509	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
1.0000E-07	5,000.0	0.02960	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
1.0000E-08	50,000.0	0.70328	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Table 12. Availability shown highlighted as a function of Element-failure rate ($B\lambda_i$) and mean time repair in hours

Availability (A) = Mean Time Between Failure (MTBF) / (MTBF + Mean Time To Repair (MTTR))

A = MTBF / (MTBF+MTTR) or MTTR = MTBF(1-A / A)

t = 17600 Hours

N = 2000

A family of curves can be created for A = 99% to 99.999% with Sys. Reliability (R) = 0.90 to 0.99999

Then MTTR is calculated @ each A value

Element Failure Rate (λ_i)	Availability (A) 72.00%	98.50%	99.00%	99.50%	99.90%	99.95%	99.99%	MTBF = 1 / N*λ_i
1.00E-07	1,944.44	76.14	50.51	25.13	5.01	2.50	0.50	5,000.00
1.00E-06	194.44	7.61	5.05	2.51	0.50	0.25	0.05	500.00
1.50E-06	129.63	5.08	3.37	1.68	0.33	0.17	0.03	333.33
1.00E-05	19.44	0.76	0.51	0.25	0.05	0.03	0.01	50.00
1.50E-05	12.96	0.51	0.34	0.17	0.03	0.02	0.00	33.33
1.00E-04	1.94	0.08	0.05	0.03	0.01	0.00	0.00	5.00
1.50E-04	1.30	0.05	0.03	0.02	0.00	0.00	0.00	3.33
1.00E-03	0.19	0.01	0.01	0.00	0.00	0.00	0.00	0.50

MTTR (Hours)

IV. Conclusion

The availability requirement must be worked by addressing the MTBF requirement, MTTR requirement, and the constraint on the number of critical-system elements (critical-parts count) for the system being designed. These requirements must be developed together and managed through out the design process with the understanding of their relationships. If a design-analysis-capability analysis such as the one discussed in this paper or the use of today's reliability and maintainability tools are used in the design, development, and evaluation (DDT&E) phase, the availability requirement, the MTTR requirement, the MTBF requirement, probability of success, affordability, and safety can all be controlled by design. However, because of their relationships to each other, availability, reliability, maintainability, and total parts count must be worked and developed together to provide the correct understanding and control to meet all of the objectives. They also must be performed during concept development and available as requirement input before proceeding with the detailed design.

Additional benefits can be achieved by selecting the best technologies that provide major reductions in total parts count. An example would be to select a direct-electro-mechanical control instead of using an intermediate fluid to perform the function while using the electro-mechanical device to control the intermediate fluid (e.g., electro-mechanical valve controlling fluid flow versus. a hydraulic or pneumatic operated valve while using a solenoid valve to control the hydraulic or pneumatic fluid which then controls the fluid valve. The use of common fluids for propulsion applications allowing an integrated system solution with only one fluid container would provide a major reduction in total parts count). When the criticality drives the design to provide redundant hardware solutions, the selection of hardware should always be at the best element reliability possible to provide the lowest maintenance burden for lowering life-cycle costs. In the provided example, additional benefits, the resultant DDT&E and operational cost will be reduced along with the achievement of the highest overall system reliability and safety and can achieve a higher availability of the system enabling mission success.

In summary, system-development work that focuses on inherent reliability, MTBF with an emphasis on parts count, and maintainability will improve performance, safety, and operational affordability. Performance is improved when fewer and better parts are used as well as provide the additional benefit of less weight. Safety is improved as hardware that does not fail during integration, checkout, and servicing inevitably will perform better in actual use. Affordability is also improved with every improvement in inherent reliability, maintainability, and focusing on reduced parts count as better overall performance makes each flight more productive and allows for additional flights due to shorter process or production intervals. Ultimately, hardware that fails during processing, regardless of redundancies, will not function well in a long flight. All that is lacking for improved technology is the investment up-front (e.g., focus on improved generic technology that numerous subsequent users can take advantage of to justify their initial investment, such as the example of selecting the best technologies mention above). This payback could be across the entire economic growth perspective and not limited to a single system use.

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