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.

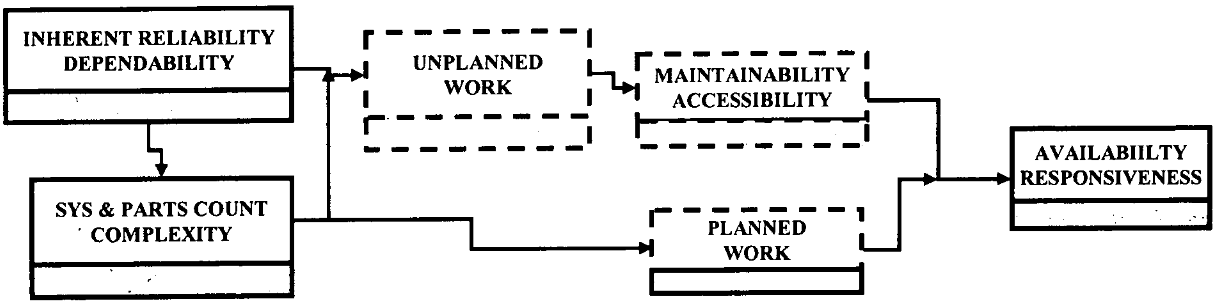

Figure 1. Availability influence diagram

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

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)

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 (λ_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.

Acknowledgments

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Constellation Program Availability Requirements Relationships

May 29, 2007

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Program Availability Requirements Relationships
Overview of the ISSUE

The following requirements from the CARD illustrate the need for a high Reliability and Available System Architecture for Lunar Operations.

Availability is classically expressed in terms of Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR).

Reliability can be expressed in terms of MTBF.

Establishing availability requirements makes it necessary to define availability and reliability with the attributes listed above. [The CARD does not adequately describe availability because it does not couple it to both of the reliability attributes; therefore, inadequately describing availability in terms of percent.]

The following analysis will:

- Show why repair time must be considered in the development of the availability requirement.
- Illustrate the sensitivity in specifying the correct values for all these attributes to achieve the program objectives.

Recommendations are provided in this presentation for changing the CARD to include all the attributes required to define the Reliability and Availability Requirements

Example Constellation Level II (CARD) Requirement Rationale That Drives Reliability and Availability

[CA5600-PO] **RIDDABLE**

- **The Constellation Architecture shall have an (TBD-001-517) % probability of launch per uncrewed launch attempt, starting at "LCC Call to Station" and ending at close of day of launch window.**

Rationale: The Lunar missions' success hinge on meeting very small Translunar Injection Windows of approximately 1 Low Earth Orbital pass per month. In order to be prepared to meet this tight window, both the uncrewed stack and the crewed stack must launch on time. Therefore, the uncrewed stack must demonstrate a High Launch Probability. This requirement decomposes into other launch availability requirements that need to be placed on the separate elements: CaLV hardware ready and LSAM hardware ready. Additionally, abort landing site weather and Launch site weather as well as the mission systems and ground systems readiness are contributing factors to the uncrewed stack launch probability. However, these are more constrained by the Crewed launch probability requirements than by this requirements. Therefore, these areas are not allocated as duplicative and less constraining requirements from this requirement.

[CA5600V-PO] **RIDDABLE**

- The ability of the Constellation Architecture to meet an (TBD-001-517) probability of launch per crew launch attempt, starting at "LCC Call to Station" and ending at close of day of launch window shall be verified by analysis. The verification analysis shall use only R&M Panel approved data sources for MTBF and MTTR and shall be performed in accordance with the CxP Reliability and Maintenance Plan (CxP 700879). Verification shall be considered successful when analysis shows that the probability of launch per crew launch attempt is at least (TBD-001-517)) with an uncertainty of not greater than (TBD-001-631).

Program Availability Requirements Relationships

INTRODUCTION of ISSUE

Constellation Program Availability Requirements Relationships

- **BACKGROUND:** An Availability Requirement by itself will not accomplish its intended function. Reference the CARD Paragraph 3.2.12 Reliability and Availability

- CARD Definition for the term: AVAILABILITY

Availability	A measure of the degree to which an item is in an operable state and can be committed for immediate use.

- Definition in Simple language: Availability is a function of the planned event flow, probability of failure to accomplish that flow, and the time required to repair.

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

- Therefore: Stating an availability requirement by itself will not accomplish the intended simple requirement.

- To enable this requirement: The Program must provide the flow-down requirements to control failure probability (MTBF) and the system repair time (MTTR) in the event of failure during the intended time period. Requirements change must start with the Program Level II CARD and flow through the Program's Level III and Level IV requirements documents down to and including the system end-item specifications.

Program Availability Requirements Relationships
CARD Availability Requirement

- Constellation Architecture Requirements Document (CARD) CxP 70000
  - Paragraph 3.2.12 Reliability and Availability
  - The Constellation Architecture system shall have an 88% (TBR-001-021) probability of launch per crew launch attempt, starting at "LCC Call to Station" and ending at close of day-of-launch window.

Table 4 - Launch Probability and Contributing Conditional Probabilities

	Crewed Launch	Cargo Launch
Net Probability of Launch:* *Range Safety Probability excluded	0.88 (TBR-001-021)	(TBD-001-064)
Contributing Conditional Probabilities:		
CEV hardware availability	0.98 (TBR-001-021)	(TBD-001-064)
CEV probability of meeting abort zone weather constraints	0.98 (TBR-001-021)	(TBD-001-064)
CLV hardware availability	0.98 (TBR-001-021)	N/A
CLV probability of meeting launch site weather constraints	0.95 (TBR-001-021)	N/A
MS hardware / system availability	TBD (TBR-001-021)	(TBD-001-064)
GS hardware / system availability	TBD (TBR-001-021)	(TBD-001-064)
CaLV hardware availability	N/A	(TBD-001-064)
CaLV probability of meeting launch site weather constraints	N/A	(TBD-001-064)
Probability of meeting Range Safety Constraints	No Spec	No Spec

Program Availability Requirements Relationships

Discussion of Requirements With Insufficient Attributes

- Develop the case using the Level II CARD requirements with the aid of Generic Reliability and Availability tools developed for deriving requirements to enable meeting the program objectives.

  (These new tools were developed for the purpose of communicating the Availability attribute relationships as well as the establishment of mathematical requirements needed to enable the Program objectives.)
  - The CARD requires a crewed launch net probability of 88% with a CLV probability of meeting launch site weather constraints of 95%
  - The CEV and CLV hardware availability of 98%
  - The MS & GS hardware / system availability is TBD

- Select the CARD availability requirement of 98% and determine with the aid of the Generic Reliability and Availability tools what the MTBF & MTTR values should be: from the charts 7 & 13 it can be determined that the Availability value alone will not determine the MTBF or the MTTR when expressed in % of MTBF (does not discriminate between different Reliability values), but establishes the relationship of the MTTR to be ~2% of the MTBF. Therefore, let us examine the CLV intended MTBF of 1000 hours (Systems reliability will be 0.999) and determine from the chart that the MTTR to be ~2% of MTBF or ~20 hours. This 20 hours exceeds the CLV stated MTTR target of 12 hours. From the chart, this MTTR of 12 hours is equivalent to an availability of ~99%. However, this assessment assumes the MTBF for the event to be the entire 1000 hours.

- Now let us examine the CEV's desired 208 days (4992 hours) for the MTBF (Using the MTBF formula on the chart the Systems Reliability is ~0.9998) and determine from the chart that the MTTR will be ~2% of MTBF or 96 hours with an availability requirement of 98%. This MTTR of 96 hours (4 days) will result in a month delay for the CEV launch for EDS rendezvous when applying the failure event time to the entire 208 days.

- The above two example MTTR results suggests a low probability of supporting the objective of launch on time need for the Lunar program and also shows MTTR does not change with respect to reliability when expressed in percent of MTBF (This relationship will be discussed later).

Program Availability Requirements Relationships

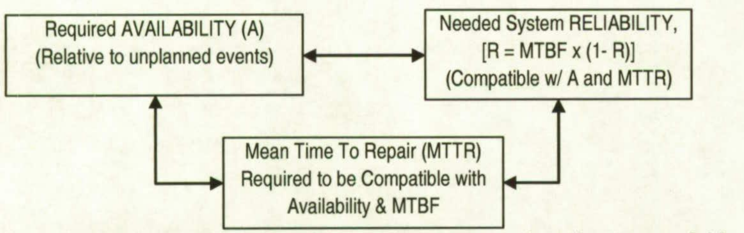
For MTTR and System Reliability Where MTBF = -1 / ln R

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

A family of curves can be created for A = 90% to 99.9% with System Reliability (R) = 0.95 to 0.9999
Then MTTR = % MTBF @ each A value

	Availability (A)												
System Reliability	90%	91%	92%	93%	94%	95%	96%	97%	**98%**	99%	**99.50%**	99.90%	**MTBF = -1/ln R**
0.9500	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	19.49573
0.9600	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	24.4966
0.9700	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	32.8308
0.9800	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	49.49832
0.9900	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	99.49916
0.9910	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	110.6104
0.9920	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	124.4993
0.9930	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	142.3566
0.9940	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	166.1662
0.9950	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	**2.0408%**	1.0101%	0.5025%	0.1001%	**199.4996**
0.9960	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	249.4997
0.9970	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	332.8331
0.9980	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	499.4998
0.9990	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	**2.0408%**	1.0101%	**0.5025%**	0.1001%	**999.4999**
0.9999	11.1111%	9.8901%	8.6957%	7.5269%	6.3830%	5.2632%	4.1667%	3.0928%	2.0408%	1.0101%	0.5025%	0.1001%	9999.5

MTTR
(in % MTBF)



Specifying one parameter implies requirements on the other two variables

Examples:
Assume the MTBF is 1000 hours (R=0.999), with an availability (A) of .98, then the MTTR would be 1000 x 2.0408% = to ~20.41 hours
Assume the desired MTTR is 4 hours with an availability of .98, then the MTBF would be 199.4996 hours @ R of 0.995
Requirement Development: Use MTBF of 1000 hours (R=0.999) and MTTR of 5 hour to support the CTS Lunar launch case; therefore, A = 0.995%

We Must Get This Right for Mission Success

Program Availability Requirements Relationships
Discussion of Proper Requirements With Appropriate Attributes

- Start with the program need to achieve its objectives of launch on time and if launch isn't achieved on 1st attempt, preserve the 24 hour turnaround. This should drive the MTTR. For this discussion our target will be 4-5 hours.
  - Assume the program's objective for the CLV is to achieve 1000 hour for its MTBF (equivalent to a System's Reliability of 0.999)
  - Therefore, from chart 12, the availability requirement must be 99.5% = ~5 hours
  - Now assume the program's objective for the CEV is to achieve 208 days or 4992 hours for its MTBF (equivalent to a Systems Reliability of ~0.9998)
  - Therefore, from chart 12, the availability requirement must be ~99.9%
  - However, when considering the hardware probability of failure of less than 5%, from charts 14 & 15, and to not over constrain the hardware parts count, this would suggest choosing the Systems Reliability value from an assessment of the System's Complexity, e.g., with System Reliability of 0.9999, the total active components count should be constrained to ~3,300 or less or if the Systems Reliability is established at 0.999 (CLV value), the total active components count should be constrained to~350 or less. This assessment assumes 1 or less failures per event and assumes the MTBF to be the entire 1000 hours.
  - This "Probability of Failure Relationship for System Complexity and System Reliability" using the active tool (product of assessment on chart 14) can be used for all Systems of the program including the Ground Systems, while considering it as a reusable system.

Program Availability Requirements Relationships
Discussion of Proper Requirements With Appropriate Attributes Continued

<u>Select MTBF of interest, "call to station until launch" (72 hrs.), and failure rate of zero (0)</u>

- With CEV MTBF of 208 days (4992 hours), driven by mission length, and CARD requirement of 88% probability of success of launch on time, the table below (see chart 22) shows that CEV's active parts are constrained to ~40,000
- With CARD Availability of 0.98, the calculated MTTR would only be ~1.5 hours for performing any corrective action during the 72 hours prior to launch.
- However, if probability of success = 95%, CEV complexity must be reduced by ~60%, i.e., total active parts count are constrained to between 10,000 and 20,000 = ~16500

		System Complexity (Parts Count (N))												
System Reliability (R)	(L)=1-R	40000	20000	10000	5000	2000	1000	500	400	300	200	100	50	25
0.9500	0.0500	100.0000%	100.0000%	99.9447%	97.6482%	77.6870%	52.7633%	31.2711%	25.9182%	20.1484%	13.9292%	7.2257%	3.6806%	1.8575%
0.9600	0.0400	100.0000%	99.9994%	99.7521%	95.0213%	69.8806%	45.1188%	25.9182%	21.3372%	16.4730%	11.3080%	5.8235%	2.9554%	1.4888%
0.9700	0.0300	100.0000%	99.9877%	98.8891%	89.4601%	59.3430%	36.2372%	20.1484%	16.4730%	12.6284%	8.6069%	4.4003%	2.2249%	1.1187%
0.9800	0.0200	99.9994%	99.7521%	95.0213%	77.6870%	45.1188%	25.9182%	13.9292%	11.3080%	8.6069%	5.8235%	2.9554%	1.4888%	0.7472%
0.9900	0.0100	99.7521%	95.0213%	77.6870%	52.7633%	25.9182%	13.9292%	7.2257%	5.8235%	4.4003%	2.9554%	1.4888%	0.7472%	0.3743%
0.9910	0.0090	99.5483%	93.2794%	74.0760%	49.0844%	23.6621%	12.6284%	6.5272%	5.2568%	3.9691%	2.6639%	1.3409%	0.6727%	0.3369%
0.9920	0.0080	99.1770%	90.9282%	69.8806%	45.1188%	21.3372%	11.3080%	5.8235%	4.6866%	3.5360%	2.3714%	1.1928%	0.5982%	0.2996%
0.9930	0.0070	98.5004%	87.7544%	65.0062%	40.8445%	18.9416%	9.9675%	5.1146%	4.1130%	3.1009%	2.0781%	1.0445%	0.5236%	0.2622%
0.9940	0.0060	97.2676%	83.4701%	59.3430%	36.2372%	16.4730%	8.6069%	4.4003%	3.5360%	2.6639%	1.7839%	0.8960%	0.4490%	0.2247%
0.9950	0.0050	95.0213%	77.6870%	52.7633%	31.2711%	13.9292%	7.2257%	3.6806%	2.9554%	2.2249%	1.4888%	0.7472%	0.3743%	0.1873%
0.9960	0.0040	90.9282%	69.8806%	45.1188%	25.9182%	11.3080%	5.8235%	2.9554%	2.3714%	1.7839%	1.1928%	0.5982%	0.2996%	0.1499%
0.9970	0.0030	83.4701%	59.3430%	36.2372%	20.1484%	8.6069%	4.4003%	2.2249%	1.7839%	1.3409%	0.8960%	0.4490%	0.2247%	0.1124%
0.9980	0.0020	69.8806%	45.1188%	25.9182%	13.9292%	5.8235%	2.9554%	1.4888%	1.1928%	0.8960%	0.5982%	0.2996%	0.1499%	0.0750%
0.9990	0.0010	45.1188%	25.9182%	13.9292%	7.2257%	2.9554%	1.4888%	**0.7472%**	0.5982%	0.4490%	0.2996%	0.1499%	0.0750%	0.0375%
0.9998	**0.0002**	**11.3080%**	**5.8235%**	**2.9554%**	**1.4888%**	**0.5982%**	**0.2996%**	**0.1499%**	**0.1199%**	**0.0900%**	**0.0600%**	**0.0300%**	**0.0150%**	**0.0075%**
0.9999	0.0001	5.8235%	2.9554%	1.4888%	0.7472%	0.2996%	0.1499%	0.0750%	0.0600%	0.0450%	0.0300%	0.0150%	0.0075%	0.0037%

Probability of Success is Highly Influenced by System Complexity !

Program Availability Requirements Relationships
Discussion of Proper Requirements With Appropriate Attributes Continued

<u>Select MTBF of interest, "call to station until launch" (72 hrs.), and failure rate of zero (0)</u>

- With CLV MTBF of 1000 hours, and CARD requirement of 88% probability of success of launch on time, the table below (see chart 25) shows that CLV's active parts are constrained from 1,000 to 2,000 = ~1780
- With CARD Availability of 0.98, the calculated MTTR would only be ~1.5 hours for performing any corrective action during the 72 hours prior to launch.
- However, if probability of success = 95%, CLV complexity must be reduced by ~60%, i.e., total active parts count are constrained to between 500 and 1000 = ~700

		System Complexity (Parts Count (N))												
System Reliability (R)	(L)=1-R	40000	20000	10000	5000	2000	1000	500	400	300	200	100	50	25
0.9500	0.0500	100.0000%	100.0000%	100.0000%	100.0000%	99.9253%	97.2676%	83.4701%	76.3072%	66.0404%	51.3248%	30.2324%	16.4730%	8.6069%
0.9600	0.0400	100.0000%	100.0000%	100.0000%	99.9999%	99.6849%	94.3865%	76.3072%	68.3996%	57.8527%	43.7858%	25.0238%	13.4112%	6.9469%
0.9700	0.0300	100.0000%	100.0000%	100.0000%	99.9980%	98.6700%	88.4675%	66.0404%	57.8527%	47.6909%	35.0791%	19.4265%	10.2372%	5.2568%
0.9800	0.0200	100.0000%	100.0000%	99.9999%	99.9253%	94.3865%	76.3072%	51.3248%	43.7858%	35.0791%	25.0238%	13.4112%	6.9469%	3.5360%
0.9900	0.0100	100.0000%	99.9999%	99.9253%	97.2676%	76.3072%	51.3248%	30.2324%	25.0238%	19.4265%	13.4112%	6.9469%	3.5360%	1.7839%
0.9910	0.0090	100.0000%	99.9998%	99.8466%	96.0836%	72.6376%	47.6909%	27.6750%	22.8331%	17.6671%	12.1553%	6.2745%	3.1881%	1.6069%
0.9920	0.0080	100.0000%	99.9990%	99.6849%	94.3865%	68.3996%	43.7858%	25.0238%	20.5784%	15.8694%	10.8812%	5.5973%	2.8389%	1.4297%
0.9930	0.0070	100.0000%	99.9958%	99.3526%	91.9540%	63.5052%	39.5891%	22.2755%	18.2578%	14.0324%	9.5886%	4.9151%	2.4885%	1.2521%
0.9940	0.0060	100.0000%	99.9823%	98.6700%	88.4675%	57.8527%	35.0791%	19.4265%	15.8694%	12.1553%	8.2773%	4.2280%	2.1368%	1.0742%
0.9950	0.0050	99.9999%	99.9253%	97.2676%	83.4701%	51.3248%	30.2324%	16.4730%	13.4112%	10.2372%	6.9469%	3.5360%	1.7839%	0.8960%
0.9960	0.0040	99.9990%	99.6849%	94.3865%	76.3072%	43.7858%	25.0238%	13.4112%	10.8812%	8.2773%	5.5973%	2.8389%	1.4297%	0.7174%
0.9970	0.0030	99.9823%	98.6700%	88.4675%	66.0404%	35.0791%	19.4265%	10.2372%	8.2773%	6.2745%	4.2280%	2.1368%	1.0742%	0.5385%
0.9980	0.0020	99.6849%	94.3865%	76.3072%	51.3248%	25.0238%	13.4112%	6.9469%	5.5973%	4.2280%	2.8389%	1.4297%	0.7174%	0.3594%
0.9990	**0.0010**	**94.3865%**	**76.3072%**	**51.3248%**	**30.2324%**	**13.4112%**	**6.9469%**	**3.5360%**	**2.8389%**	**2.1368%**	**1.4297%**	**0.7174%**	**0.3594%**	**0.1798%**
0.9998	0.0002	43.7858%	25.0238%	13.4112%	6.9469%	2.8389%	1.4297%	0.7174%	0.5743%	0.4311%	0.2876%	0.1439%	0.0720%	0.0360%
0.9999	0.0001	25.0238%	13.4112%	6.9469%	3.5360%	1.4297%	0.7174%	0.3594%	0.2876%	0.2158%	0.1439%	0.0720%	0.0360%	0.0180%

Probability of Success is Highly Influenced by System Complexity !

Program Availability Requirements Relationships

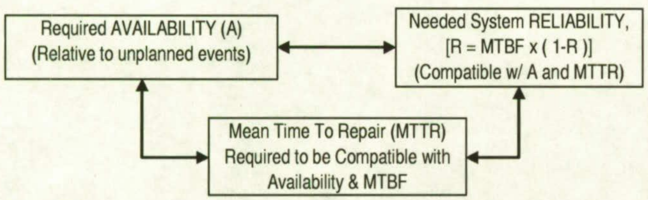
For MTTR and System Reliability Where MTBF = -1 / ln R

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

A family of curves can be created for A = 90% to 99.9% with System Reliability (R) = 0.95 to 0.9999
Then MTTR is calculated for @ each A value

	Availability (A)												
System Reliability	90%	91%	92%	93%	94%	95%	96%	97%	**98%**	99%	**99.50%**	99.90%	**MTBF = -1/ln R**
0.9500	2.17	1.93	1.70	1.47	1.24	1.03	0.81	0.60	0.40	0.20	0.10	0.02	19.49573
0.9600	2.72	2.42	2.13	1.84	1.56	1.29	1.02	0.76	0.50	0.25	0.12	0.02	24.4966
0.9700	3.65	3.25	2.85	2.47	2.10	1.73	1.37	1.02	0.67	0.33	0.16	0.03	32.8308
0.9800	5.50	4.90	4.30	3.73	3.16	2.61	2.06	1.53	1.01	0.50	0.25	0.05	49.49832
0.9900	11.06	9.84	8.65	7.49	6.35	5.24	4.15	3.08	2.03	1.01	0.50	0.10	99.49916
0.9910	12.29	10.94	9.62	8.33	7.06	5.82	4.61	3.42	2.26	1.12	0.56	0.11	110.6104
0.9920	13.83	12.31	10.83	9.37	7.95	6.55	5.19	3.85	2.54	1.26	0.63	0.12	124.4993
0.9930	15.82	14.08	12.38	10.72	9.09	7.49	5.93	4.40	2.91	1.44	0.72	0.14	142.3566
0.9940	18.46	16.43	14.45	12.51	10.61	8.75	6.92	5.14	3.39	1.68	0.84	0.17	166.1662
0.9950	22.17	19.73	17.35	15.02	12.73	10.50	8.31	6.17	**4.07**	2.02	1.00	0.20	**199.4996**
0.9960	27.72	24.68	21.70	18.78	15.93	13.13	10.40	7.72	5.09	2.52	1.25	0.25	249.4997
0.9970	36.98	32.92	28.94	25.05	21.24	17.52	13.87	10.29	6.79	3.36	1.67	0.33	332.8331
0.9980	55.50	49.40	43.43	37.60	31.88	26.29	20.81	15.45	10.19	5.05	2.51	0.50	499.4998
0.9990	111.06	98.85	86.91	75.23	63.80	52.61	41.65	30.91	**20.40**	10.10	**5.02**	1.00	**999.4999**
0.9999	1,111.06	988.96	869.52	752.65	638.27	526.29	416.65	309.26	204.07	101.01	50.25	10.01	9999.5

MTTR



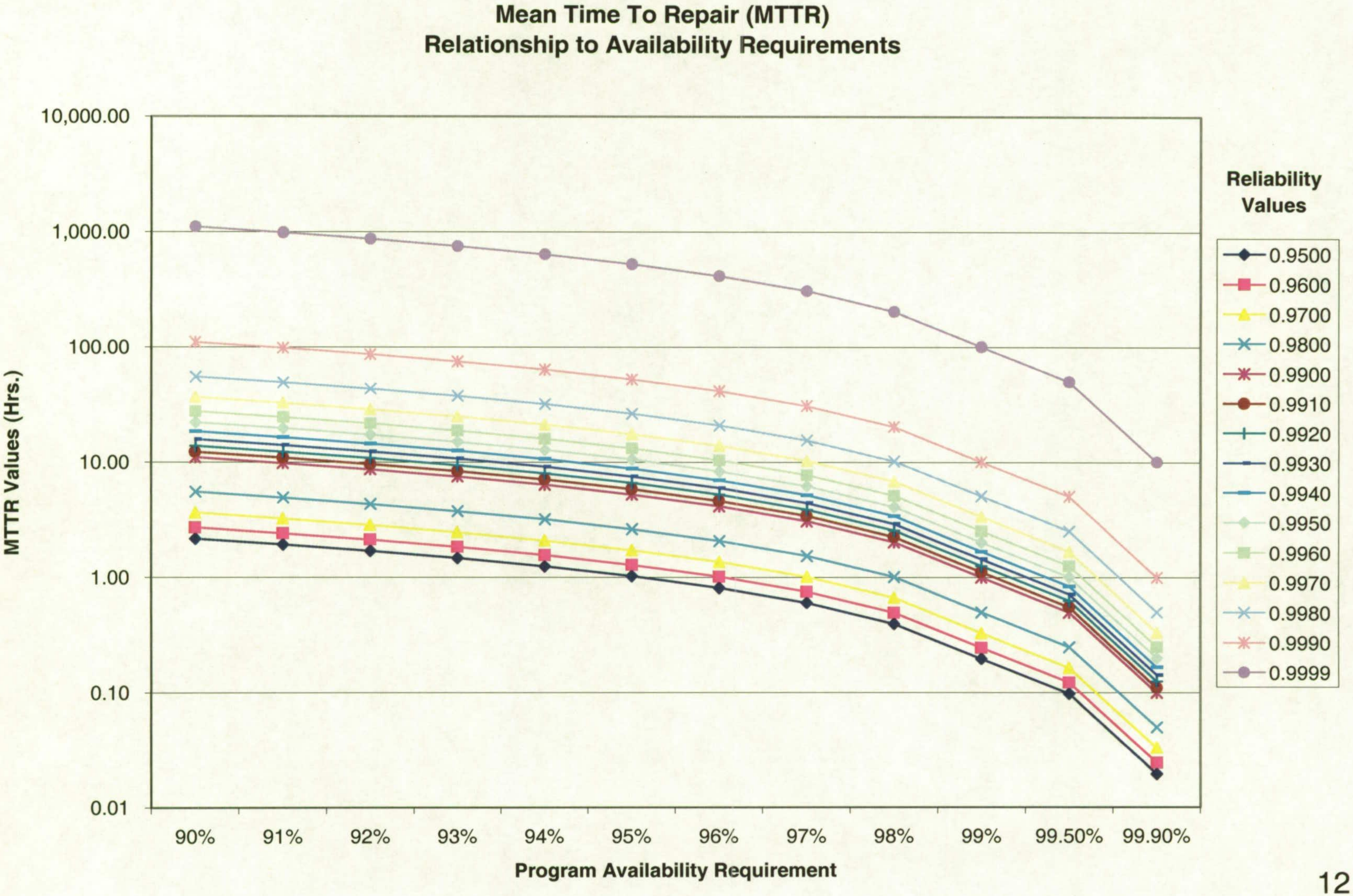
Specifying one parameter implies requirements on the other two variables

Examples:
Assume the MTBF is 1000 hours (R=0.999), with an availability (A) of .98, then the MTTR would be 20.4 hours
Assume the desired MTTR is ~4 hours with an availability of .98, then the MTBF would be ~199.5 hours @ R of 0.995
Requirement Development: Use MTBF of 1000 hours (R=0.999) and MTTR of 5 hour to support the CTS Lunar launch case; therefore, A = 0.995 or 99.5%

We Must Get This Right for Mission Success

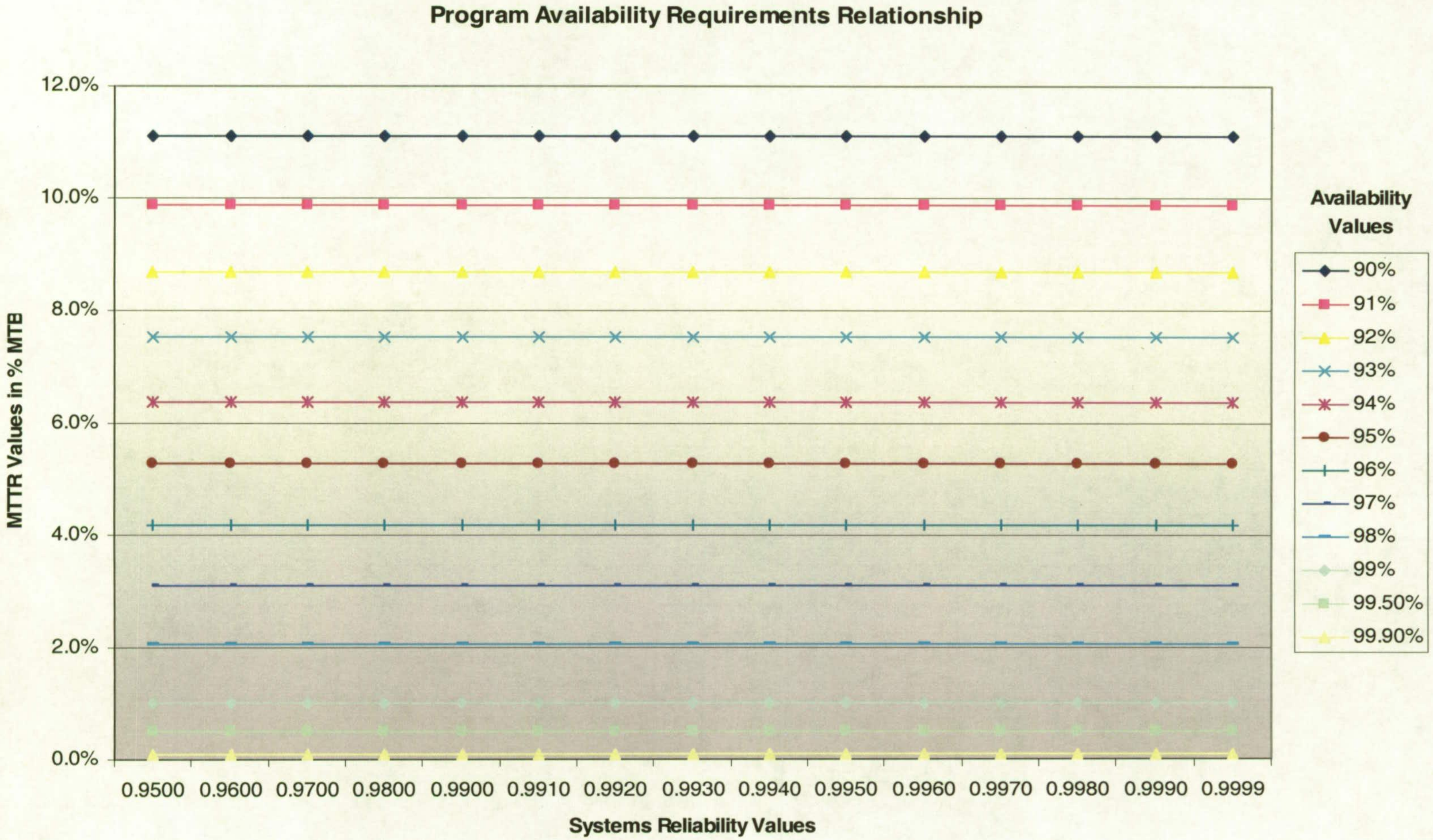
Program Availability Requirements Relationships

For MTTR and System Reliability Where MTBF = -1 / ln R



Program Availability Requirements Relationships

For MTTR and System Reliability Where MTBF = R / 1 - R



Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity and System Reliability Where MTBF = R / 1 - R

Maximum number of failures = 1 or less (r) = [1] N*L*t

Failure rate of each system element (L for Lambda) = 1 - R   t = 1 [1]

Note: Red Font Cells in Row 4 & 5 are variables and can be changed to meet your application's needs.

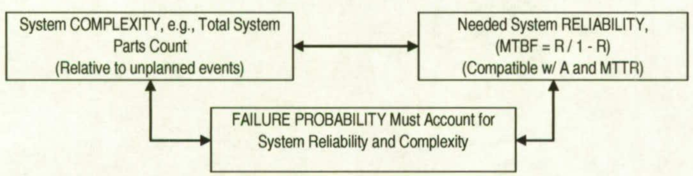
A family of curves can be created for Probability of Failure of 2 or More Parts per event with System Reliability Values of: (R) = 0.95 to 0.9999

System Complexity (Parts Count (N))

System Reliability (R)	(L)=1-R	20000	10000	5000	2000	1000	500
0.9500	0.0500	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%
0.9600	0.0400	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%
0.9700	0.0300	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	99.9995%
0.9800	0.0200	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	99.9501%
0.9900	0.0100	100.0000%	100.0000%	100.0000%	100.0000%	99.9501%	95.9572%
0.9910	0.0090	100.0000%	100.0000%	100.0000%	100.0000%	99.8766%	93.8901%
0.9920	0.0080	100.0000%	100.0000%	100.0000%	99.9998%	99.6981%	90.8422%
0.9930	0.0070	100.0000%	100.0000%	100.0000%	99.9988%	99.2705%	86.4112%
0.9940	0.0060	100.0000%	100.0000%	100.0000%	99.9920%	98.2649%	80.0852%
0.9950	0.0050	100.0000%	100.0000%	100.0000%	99.9501%	95.9572%	71.2703%
0.9960	0.0040	100.0000%	100.0000%	100.0000%	99.6981%	90.8422%	59.3994%
0.9970	0.0030	100.0000%	100.0000%	99.9995%	98.2649%	80.0852%	44.2175%
0.9980	0.0020	100.0000%	100.0000%	99.9501%	90.8422%	59.3994%	26.4241%
0.9990	0.0010	100.0000%	99.9501%	95.9572%	59.3994%	26.4241%	**9.0204%**
0.9999	0.0001	59.3994%	26.4241%	9.0204%	1.7523%	0.4679%	0.1209%

System Reliability (R)	(L)=1-R	400	300	200	100	50	25
0.9500	0.0500	100.0000%	99.9995%	99.9501%	95.9572%	71.2703%	35.5364%
0.9600	0.0400	99.9998%	99.9920%	99.6981%	90.8422%	59.3994%	26.4241%
0.9700	0.0300	99.9920%	99.8766%	98.2649%	80.0852%	44.2175%	17.3359%
0.9800	0.0200	99.6981%	98.2649%	90.8422%	59.3994%	26.4241%	9.0204%
0.9900	0.0100	90.8422%	80.0852%	59.3994%	26.4241%	9.0204%	2.6499%
0.9910	0.0090	87.4311%	75.1340%	53.7163%	22.7518%	7.5439%	2.1818%
0.9920	0.0080	82.8799%	69.1559%	47.5069%	19.1208%	6.1552%	1.7523%
0.9930	0.0070	76.8922%	62.0385%	40.8167%	15.5805%	4.8671%	1.3638%
0.9940	0.0060	69.1559%	53.7163%	33.7373%	12.1901%	3.6936%	1.0186%
0.9950	0.0050	59.3994%	44.2175%	26.4241%	9.0204%	2.6499%	0.7191%
0.9960	0.0040	47.5069%	33.7373%	19.1208%	6.1552%	1.7523%	0.4679%
0.9970	0.0030	33.7373%	22.7518%	12.1901%	3.6936%	1.0186%	0.2676%
0.9980	0.0020	19.1208%	12.1901%	6.1552%	1.7523%	0.4679%	0.1209%
0.9990	0.0010	6.1552%	3.6936%	1.7523%	0.4679%	0.1209%	0.0307%
0.9999	0.0001	0.0779%	0.0441%	0.0197%	0.0050%	0.0012%	0.0003%

Probability of a Failure of 2 or More Parts During the Event



Specifying one parameter implies requirements on the other two variables

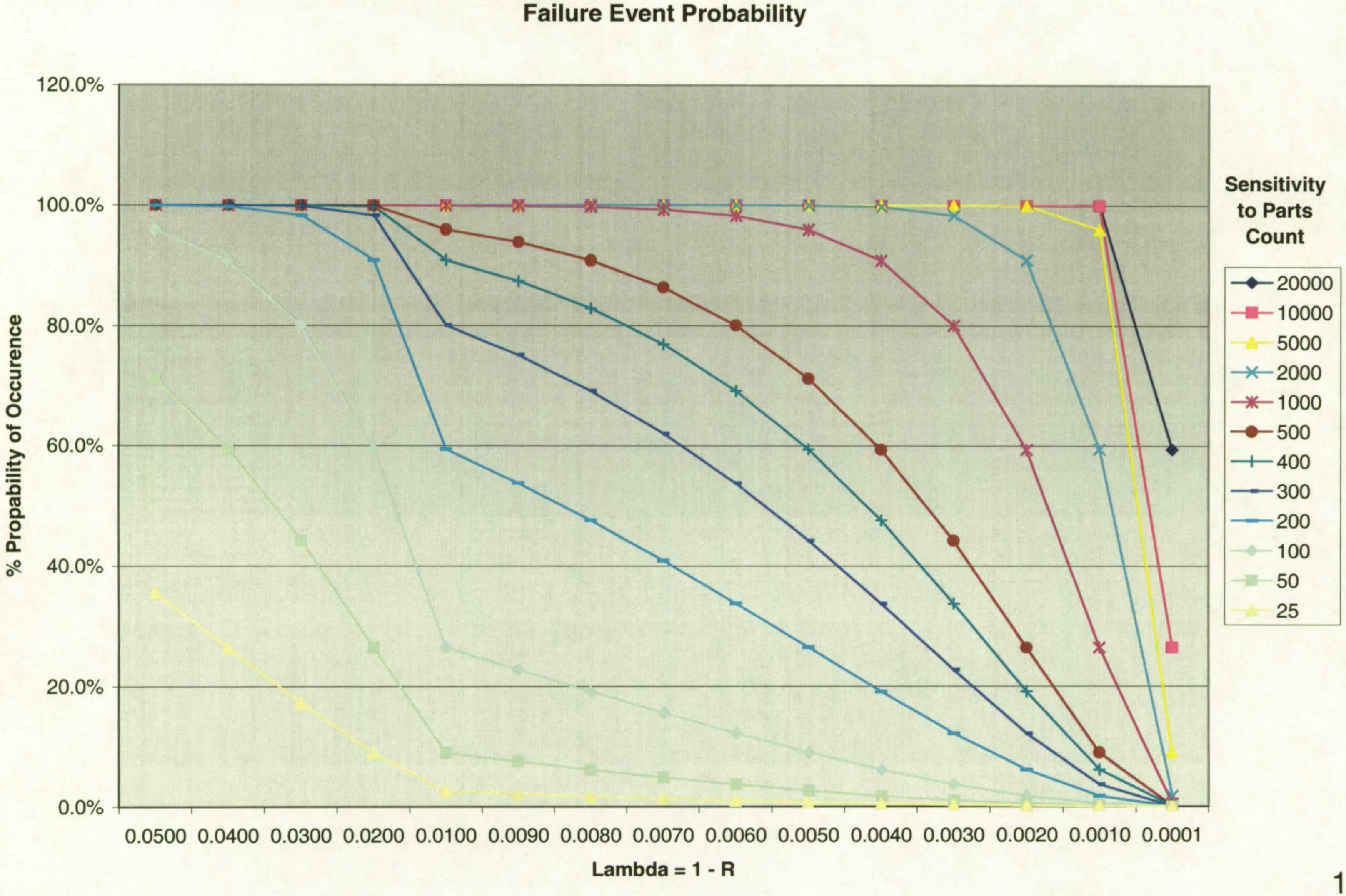
Examples:
Assume the R=0.999 or less, with an availability (A) of .98, then the MTTR would be 1000 x 2.0408% = to ~20.41 hours; however, Event Failure is extremely high relative to a given System Complexity.

Requirement Development: The Reliability-to-System Complexity Relationship must be Developed with Compatable Requirements to enable Mission Success

We Must Get This Right for Mission Success

Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity and System Reliability Where MTBF = R / 1 - R



Program Availability Requirements Relationships
Conclusions

- The Constellation Program must change and expand the Reliability and Availability Requirements by selecting derived values from the Program objectives and include requirements for MTBF, MTTR, and Probability of Failure to Launch tied to Total System Complexity [Total number of systems and active components, e.g., any replaceable component (LRU's) at the launch site].

- The development of attributes required for the Lunar example should consider using these active assessment tools in establishing the Availability, MTBF, MTTR and System's Complexity constraints.

- Desire is to achieve a high probability of launch on time; therefore, if launch isn't achieved on 1st attempt, the program needs to preserve the 24 hour turnaround which then drives the MTTR to 5 hours or less.
  - Therefore, from chart 12, the availability requirement for the CLV must be 99.5% = ~5 hours
  - Now assume the program's objective for the CEV is to achieve 208 days or 4992 hours for its MTBF (equivalent to a Systems Reliability of ~0.9998)
  - Therefore, from chart 12, the availability requirement must be ~99.9%

Program Availability Requirements Relationships

Conclusions

- However, when considering the hardware probability of failure of less than 5%, from charts 14 & 15 this would suggest choosing the System Reliability value from an assessment of the System's Complexity, e.g., with System Reliability of 0.9999 (equivalent to a MTBF of 9999.5 hours) for both the CLV & CEV, the total active components count should be constrained to ~3,300 or less. This assessment allows for 1 or less failures per event. Example: Reset tool to 0 failures allowed, this yields a system complexity constrained from the ~3300 to only ~500.

- MTTR does not change with respect to reliability when expressed in percent of MTBF (see chart 13); however, actual MTTR values proportionally increase with system reliability values (see chart 12) while holding the Availability value constant, i.e., to hold MTTR constant the system reliability must improve to achieve higher availability resulting in higher probability of launch success.

- This "Probability of Failure Relationship for System Complexity and System Reliability" can be accomplished using the assessment tools (product of assessment on chart 14) to evaluate all systems of the program including the ground systems when considering it as a reusable system.

Program Availability Requirements Relationships

Recommendations

- Establish the probability of launch value, starting at "LCC Call to Station" and ending at close of day of launch window, such that the weather constraint of 0.95 becomes the driver and not the Flight or Ground Systems hardware failure probability.

- Revise the CARD requirement for Net Probability of Launch to 0.95.

- Establish a requirement in the CARD for MTTR for CLV & CEV of ~5 hrs or less.

- Establish the Ground and Mission Systems reliability requirements and active hardware limitations that are compatible with the Program objectives and the revised CARD requirements for launch probability.

- Constrain CEV/CLV/MS/GS System Complexity (See following charts for suggested requirements)

Program Availability Requirements Relationships
Recommendations – For CEV

- Accept the Flight Systems hardware reliability values of 0.9998 for CEV (equivalent to MTBF of 208 days)

- Establish the Availability value for the CEV (assuming 0.9998 reliability) to be 99.9%

Assuming the CARD Baseline: Probability of launch, from "LCC Call to Station" to launch

- Add new requirement to constrain the total active components count to an equivalent ~16,500 or less @ the Systems Reliability of 0.9998 for the CEV and with a 95% probability of launch. This assessment allows for 0 failures per event while assuming a 72 hr. launch period

If the desire is to broaden the launch period of interest: Probability of launch, from Vehicle Stacking to Launch

- Add new requirement to constrain the total active components count to an equivalent ~2,575 or less @ the Systems Reliability of 0.9998 for the CEV and with a 95% probability of launch. This assessment allows for 0 failures per event while assuming a ~500 hr. launch site flow period
- Or, add new requirement to constrain the total active components count to an equivalent ~17,300 or less @ the Systems Reliability of 0.9998 for the CEV and with a 95% probability of launch. This assessment allows for one or less failures per event while assuming a ~500 hr. launch site flow period

Program Availability Requirements Relationships

Recommendations – For CLV

- Accept the Flight Systems hardware reliability values of 0.999 for CLV (equivalent to MTBF of 1000 hrs)

- Establish the Availability value for the CLV (assuming 0.999 reliability) to be 99.5%

Assuming the CARD Baseline: Probability of launch, from "LCC Call to Station" to launch

- Add new requirement to constrain the total active components count to an equivalent ~700 or less @ the Systems Reliability of 0.999 for the CLV and with a 95% probability of launch. This assessment allows for 0 failures per event while assuming a 72 hr. launch period

If the desire is to broaden the launch period of interest: Probability of launch, from Vehicle Stacking to Launch

- Add new requirement to constrain the total active components count to an equivalent ~100 or less @ the Systems Reliability of 0.999 for the CLV and with a 95% probability of launch. This assessment allows for 0 failures per event while assuming a ~500 hr. launch site flow period
- Or, add new requirement to constrain the total active components count to an equivalent ~675 or less @ the Systems Reliability of 0.999 for the CLV and with a 95% probability of launch. This assessment allows for one or less failures per event while assuming a ~500 hr. launch site flow period

Program Availability Requirements Relationships

APPENDIX

Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity & System Reliability Where CEV MTBF of Interest = Last 72 hrs to Launch

Maximum number of failures = 1 or less (r) = [0] N*L*t t = 1

Failure rate of each system element (L for Lambda) = 1 - R [0.015]

Note: Red Font Cells in Row 4 & 5 are variables and can be changed to meet your application's needs.

A family of curves can be created for Probability of Failure of 0 Parts per event with System Reliability Values of: (R) = 0.95 to 0.9999 (CEV @ 0.9998) or 208 days = MTBF

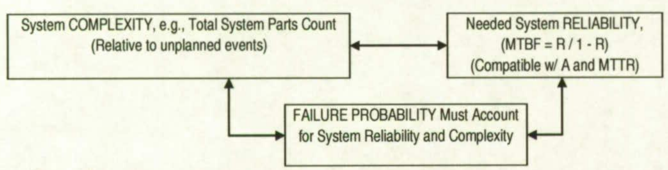
System Complexity (Parts Count (N))

System Reliability (R)	(L)=1-R	40000	20000	10000	5000	2000	1000	500	400	300	200	100	50	25
0.9500	0.0500	100.0000%	100.0000%	99.9447%	97.6482%	77.6870%	52.7633%	31.2711%	25.9182%	20.1484%	13.9292%	7.2257%	3.6806%	1.8575%
0.9600	0.0400	100.0000%	99.9994%	99.7521%	95.0213%	69.8806%	45.1188%	25.9182%	21.3372%	16.4730%	11.3080%	5.8235%	2.9554%	1.4888%
0.9700	0.0300	100.0000%	99.9877%	98.8891%	89.4601%	59.3430%	36.2372%	20.1484%	16.4730%	12.6284%	8.6069%	4.4003%	2.2249%	1.1187%
0.9800	0.0200	99.9994%	99.7521%	95.0213%	77.6870%	45.1188%	25.9182%	13.9292%	11.3080%	8.6069%	5.8235%	2.9554%	1.4888%	0.7472%
0.9900	0.0100	99.7521%	95.0213%	77.6870%	52.7633%	25.9182%	13.9292%	7.2257%	5.8235%	4.4003%	2.9554%	1.4888%	0.7472%	0.3743%
0.9910	0.0090	99.5483%	93.2794%	74.0760%	49.0844%	23.6621%	12.6284%	6.5272%	5.2568%	3.9691%	2.6639%	1.3409%	0.6727%	0.3369%
0.9920	0.0080	99.1770%	90.9282%	69.8806%	45.1188%	21.3372%	11.3080%	5.8235%	4.6866%	3.5360%	2.3714%	1.1928%	0.5982%	0.2996%
0.9930	0.0070	98.5004%	87.7544%	65.0062%	40.8445%	18.9416%	9.9675%	5.1146%	4.1130%	3.1009%	2.0781%	1.0445%	0.5236%	0.2622%
0.9940	0.0060	97.2676%	83.4701%	59.3430%	36.2372%	16.4730%	8.6069%	4.4003%	3.5360%	2.6639%	1.7839%	0.8960%	0.4490%	0.2247%
0.9950	0.0050	95.0213%	77.6870%	52.7633%	31.2711%	13.9292%	7.2257%	3.6806%	2.9554%	2.2249%	1.4888%	0.7472%	0.3743%	0.1873%
0.9960	0.0040	90.9282%	69.8806%	45.1188%	25.9182%	11.3080%	5.8235%	2.9554%	2.3714%	1.7839%	1.1928%	0.5982%	0.2996%	0.1499%
0.9970	0.0030	83.4701%	59.3430%	36.2372%	20.1484%	8.6069%	4.4003%	2.2249%	1.7839%	1.3409%	0.8960%	0.4490%	0.2247%	0.1124%
0.9980	0.0020	69.8806%	45.1188%	25.9182%	13.9292%	5.8235%	2.9554%	1.4888%	1.1928%	0.8960%	0.5982%	0.2996%	0.1499%	0.0750%
0.9990	0.0010	45.1188%	25.9182%	13.9292%	7.2257%	2.9554%	1.4888%	**0.7472%**	0.5982%	0.4490%	0.2996%	0.1499%	0.0750%	0.0375%
0.9998	**0.0002**	**11.3080%**	**5.8235%**	**2.9554%**	**1.4888%**	**0.5982%**	**0.2996%**	**0.1499%**	**0.1199%**	**0.0900%**	**0.0600%**	**0.0300%**	**0.0150%**	**0.0075%** <-----
0.9999	0.0001	5.8235%	2.9554%	1.4888%	0.7472%	0.2996%	0.1499%	0.0750%	0.0600%	0.0450%	0.0300%	0.0150%	0.0075%	0.0037%

This example uses the 208 day or 4992 hour MTBF for the CEV and the Constellation's 88% probability of success (yellow fill color) and the actual MTBF value was 4999 hours = to 0.9998 Reliability of the weakest component while assuming 0 failures during the call-to-station until launch period of 72 hours.

Probability of a Failure of 0 Parts During the Event fot This CEV Example

These example results for the "208 day or 4992 hour MTBF for the CEV and the Constellation's 88% probability of success (yellow fill color) while assuming 0 failures during the call-to-station until launch period of 72 hours" will constrain the total active parts count to ~40,000; however, if the desire is to provide a propability of sucess of 95%, the total active parts count would be constrained to between 10,000 and 20,000 = ~1650. If the CARD Availability requirement (0.98), the MTTR would be 1.5 hours, but would relax the parts count



Specifying one parameter implies requirements on the other two variables

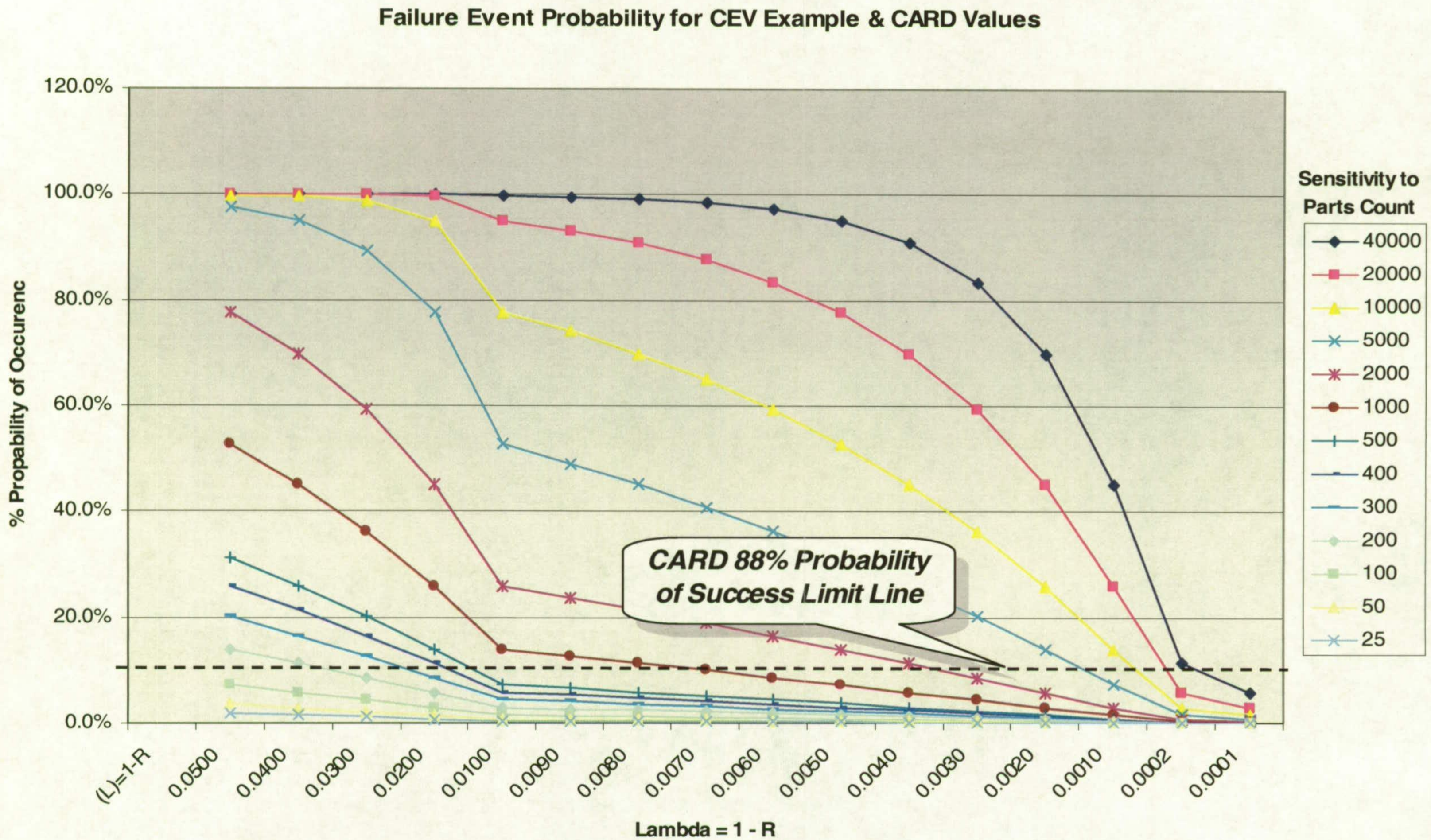
Examples:
Assume the R=0.999 or less, with an availability (A) of .98, then the MTTR would be 1000 x 2.0408% = to ~20.41 hours; however, Event Failure is extremely high relative to a given System Complexity.

Requirement Development: The Reliability-to-System Complexity Relationship must be Developed with Compatable Requirements to enable Mission Success

We Must Get This Right for Mission Success

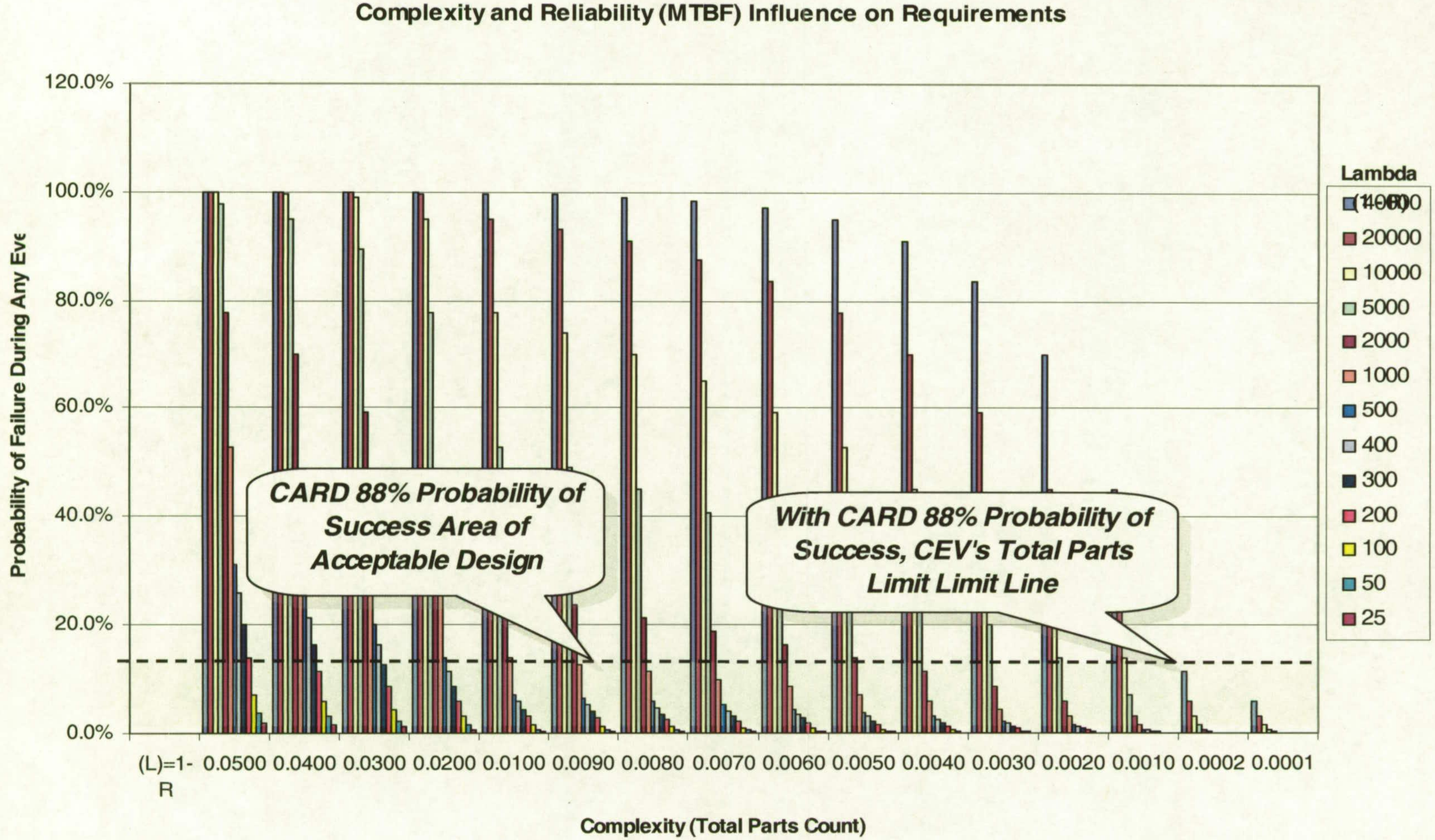
Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity & System Reliability Where CEV MTBF of Interest = Last 72 hrs to Launch



Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity & System Reliability Where CEV MTBF of Interest = Last 72 hrs to Launch



Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity & System Reliability Where CLV MTBF of Interest = Last 72 hrs to Launch

Maximum number of failures = 1 or less (r) = 0 N*L*t

Failure rate of each system element (L for Lambda) = 1 - R t = 1 0.072

Note: Red Font Cells in Row 4 & 5 are variables and can be changed to meet your application's needs.

A family of curves can be created for Probability of Failure of 0 Parts per event with System Reliability Values of: (R) = 0.95 to 0.9999 (CLV @ 0.999) or 1000 hours = MTBF

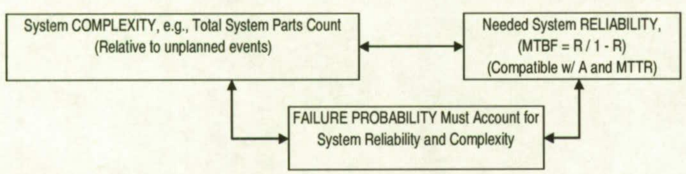
System Complexity (Parts Count (N))

System Reliability (R)	(L)=1-R	40000	20000	10000	5000	2000	1000	500	400	300	200	100	50	25
0.9500	0.0500	100.0000%	100.0000%	100.0000%	100.0000%	99.9253%	97.2676%	83.4701%	76.3072%	66.0404%	51.3248%	30.2324%	16.4730%	8.6069%
0.9600	0.0400	100.0000%	100.0000%	100.0000%	99.9999%	99.6849%	94.3865%	76.3072%	68.3996%	57.8527%	43.7858%	25.0238%	13.4112%	6.9469%
0.9700	0.0300	100.0000%	100.0000%	100.0000%	99.9980%	98.6700%	88.4675%	66.0404%	57.8527%	47.6909%	35.0791%	19.4265%	10.2372%	5.2568%
0.9800	0.0200	100.0000%	100.0000%	99.9999%	99.9253%	94.3865%	76.3072%	51.3248%	43.7858%	35.0791%	25.0238%	13.4112%	6.9469%	3.5360%
0.9900	0.0100	100.0000%	99.9999%	99.9253%	97.2676%	76.3072%	51.3248%	30.2324%	25.0238%	19.4265%	13.4112%	6.9469%	3.5360%	1.7839%
0.9910	0.0090	100.0000%	99.9998%	99.8466%	96.0836%	72.6376%	47.6909%	27.6750%	22.8331%	17.6671%	12.1553%	6.2745%	3.1881%	1.6069%
0.9920	0.0080	100.0000%	99.9990%	99.6849%	94.3865%	68.3996%	43.7858%	25.0238%	20.5784%	15.8694%	10.8812%	5.5973%	2.8389%	1.4297%
0.9930	0.0070	100.0000%	99.9958%	99.3526%	91.9540%	63.5052%	39.5891%	22.2755%	18.2578%	14.0324%	9.5886%	4.9151%	2.4885%	1.2521%
0.9940	0.0060	100.0000%	99.9823%	98.6700%	88.4675%	57.8527%	35.0791%	19.4265%	15.8694%	12.1553%	8.2773%	4.2280%	2.1368%	1.0742%
0.9950	0.0050	99.9999%	99.9253%	97.2676%	83.4701%	51.3248%	30.2324%	16.4730%	13.4112%	10.2372%	6.9469%	3.5360%	1.7839%	0.8960%
0.9960	0.0040	99.9990%	99.6849%	94.3865%	76.3072%	43.7858%	25.0238%	13.4112%	10.8812%	8.2773%	5.5973%	2.8389%	1.4297%	0.7174%
0.9970	0.0030	99.9823%	98.6700%	88.4675%	66.0404%	35.0791%	19.4265%	10.2372%	8.2773%	6.2745%	4.2280%	2.1368%	1.0742%	0.5385%
0.9980	0.0020	99.6849%	94.3865%	76.3072%	51.3248%	25.0238%	13.4112%	6.9469%	5.5973%	4.2280%	2.8389%	1.4297%	0.7174%	0.3594%
0.9990	**0.0010**	**94.3865%**	**76.3072%**	**51.3248%**	**30.2324%**	**13.4112%**	**6.9469%**	**3.5360%**	**2.8389%**	**2.1368%**	**1.4297%**	**0.7174%**	**0.3594%**	**0.1798%** <-----
0.9998	0.0002	43.7858%	25.0238%	13.4112%	6.9469%	2.8389%	1.4297%	0.7174%	0.5743%	0.4311%	0.2876%	0.1439%	0.0720%	0.0360%
0.9999	0.0001	25.0238%	13.4112%	6.9469%	3.5360%	1.4297%	0.7174%	0.3594%	0.2876%	0.2158%	0.1439%	0.0720%	0.0360%	0.0180%

This example uses the 1000 hour MTBF for the CLV and the Constellation's 88% probability of success (green fill color) and the actual MTBF value was 999 hours = to 0.999 Reliability of the weakest component while assuming 0 failures during the call-to-station until launch period of 72 hours.

Probability of a Failure of 0 Parts During the Event fot This CLV Example

These example results for the "1000 hours MTBF for the CLV and the Constellation's 88% probability of success (green fill color) while assuming 0 failures during the call-to-station until launch period of 72 hours" will constrain the total active parts count to ~1,780; however, if the desire is to provide a propability of sucess of 95%, the total active parts count would be constrained to between 500 and 1,000 or ~700.



Specifying one parameter implies requirements on the other two variables

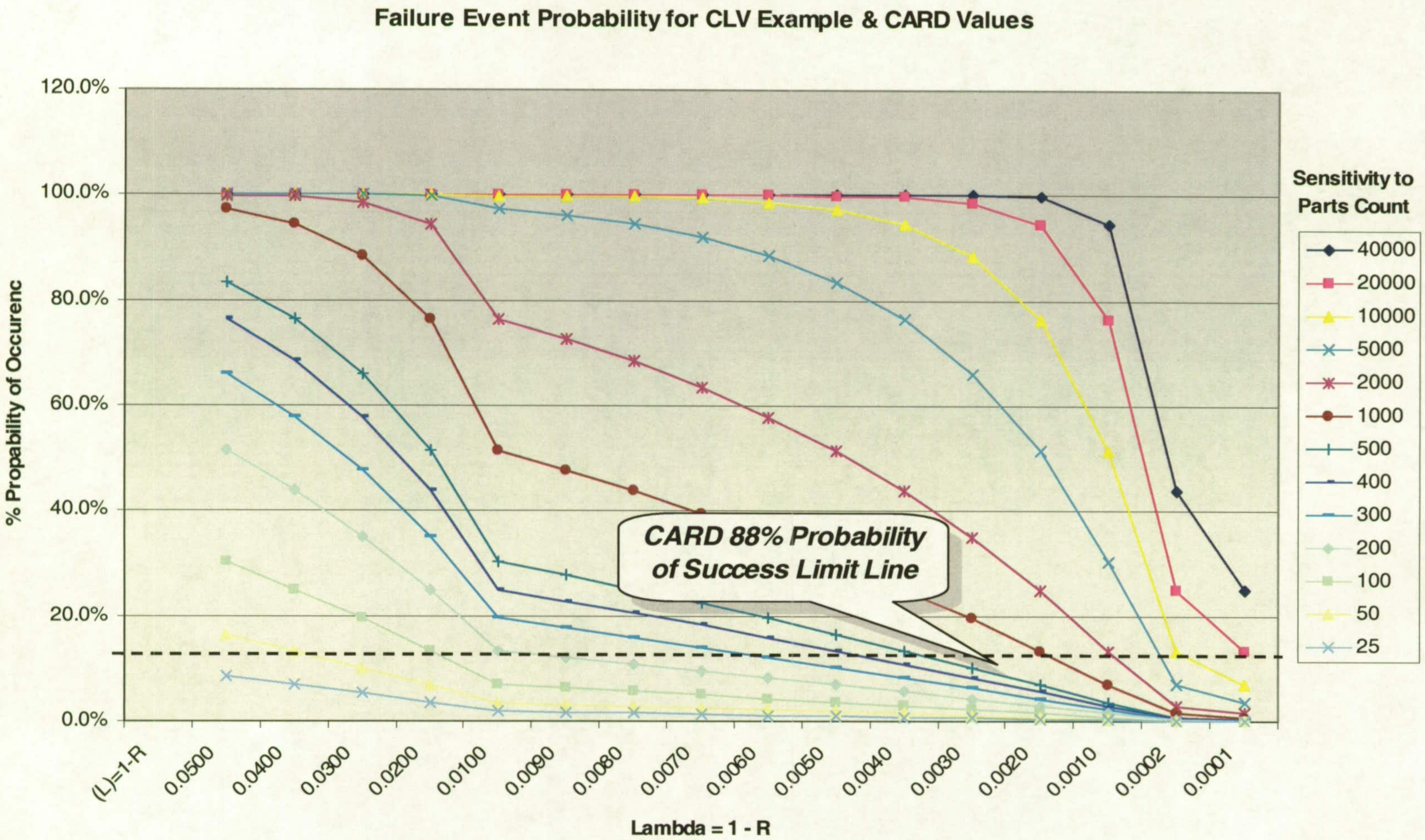
Examples:
Assume the R=0.999 or less, with an availability (A) of .98, then the MTTR would be 1000 x 2.0408% = to ~20.41 hours; however, Event Failure is extremely high relative to a given System Complexity. For this case of only 72 hour = MTBF of interest, the MTTR is 1.5 hours.

Requirement Development: The Reliability-to-System Complexity Relationship must be Developed with Compatable Requirements to enable Mission Success

We Must Get This Right for Mission Success

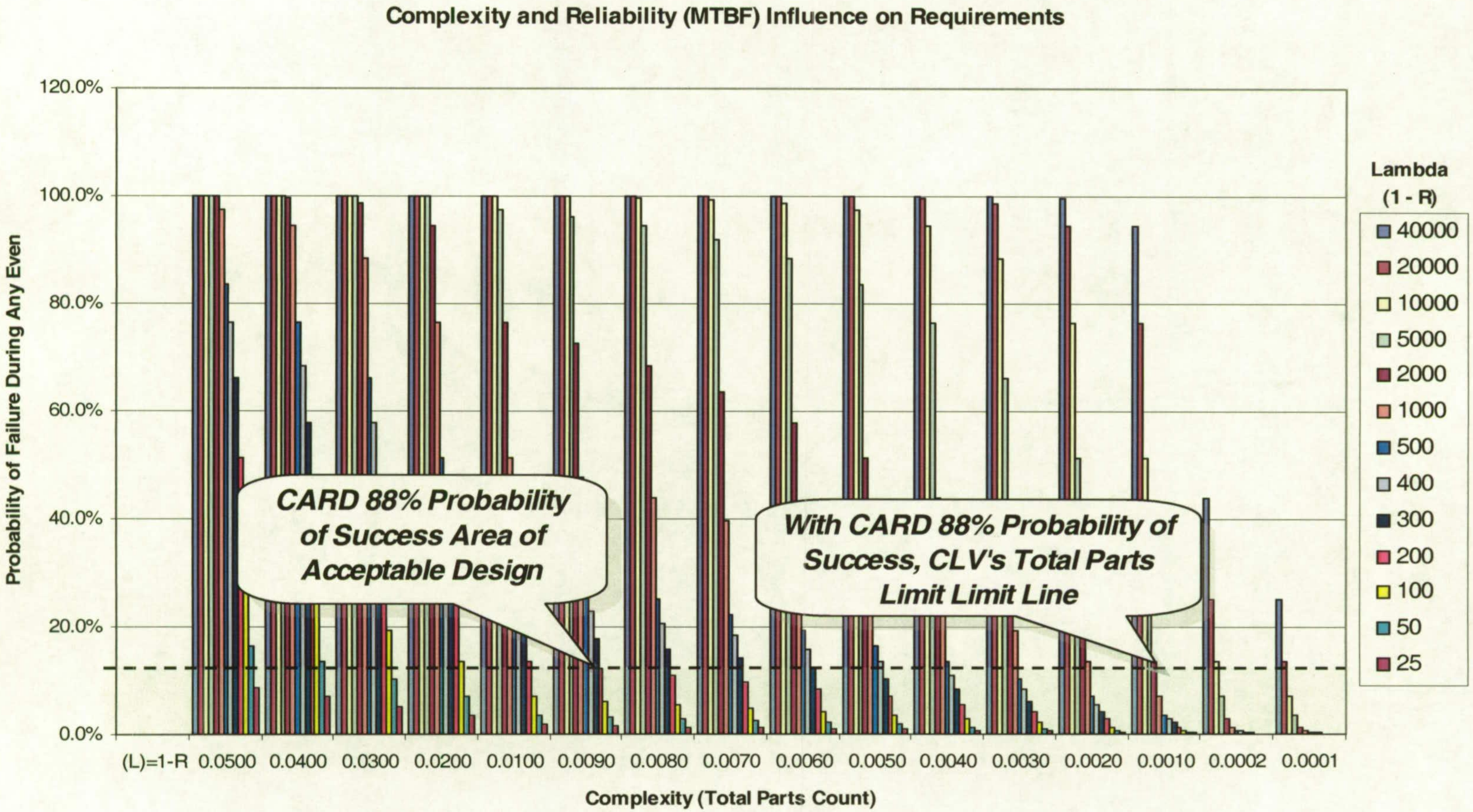
Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity & System Reliability Where CEV MTBF of Interest = Last 72 hrs to Launch



Program Availability Requirements Relationships

Probability of Failure Relationship for System Complexity & System Reliability Where CEV MTBF of Interest = Last 72 hrs to Launch



SPST "FRESH" PERSPECTIVE
FOCUSING ON KEY STS OBJECTIVES

Propulsion System Choices and Their Pros & Cons:*

Prepared By: Mr. Russell Joyner, Pratt & Whitney

May 21st 2003 - SPST Annual Meeting

* A Product of the SPST Functional Requirements Sub-team

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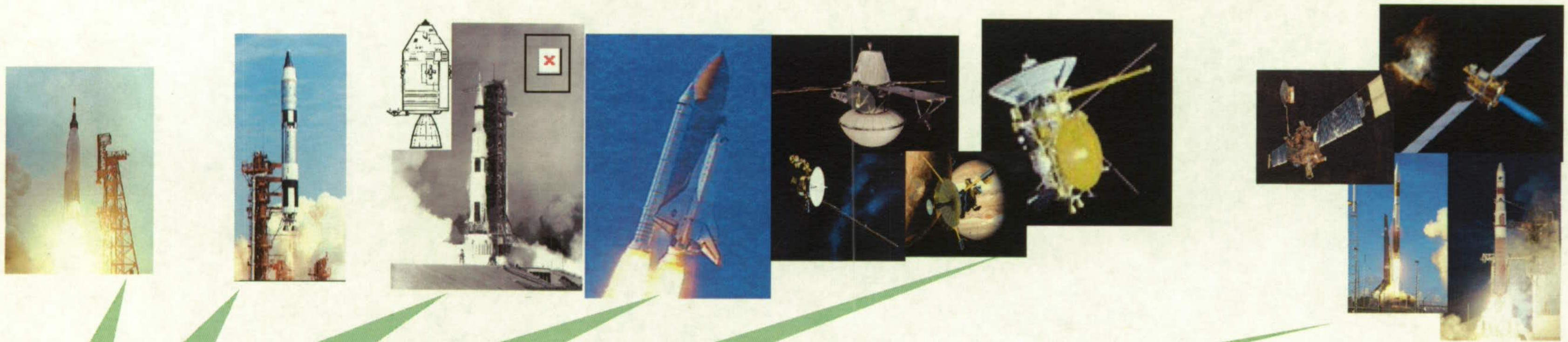
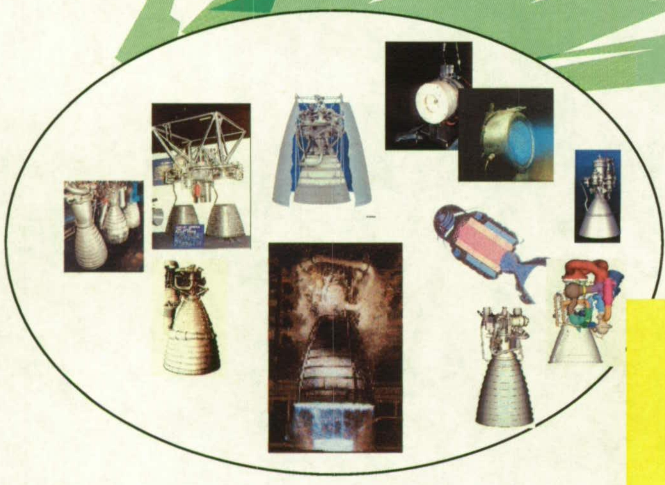
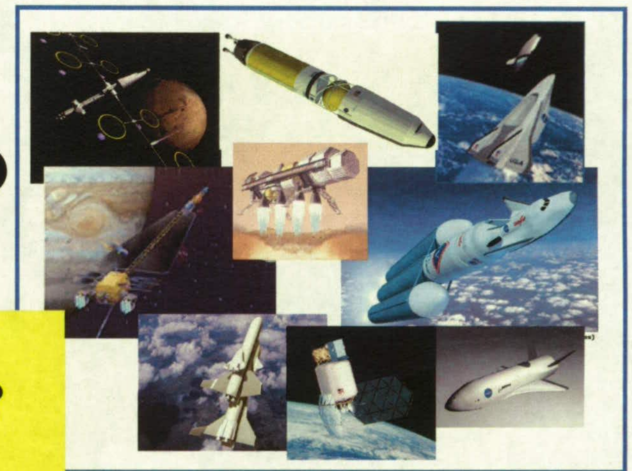
A History of Designs ..
Many Choices Exist for Future Missions ... 1st Order Guidance?







What Does The Designer Choose ? How Do We Help His/Her Selection ?

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Introduction : Propulsion System Design Has A Major Influence

In defining a space vehicle architecture, the propulsion system and related sub systems choices selected will have a major influence on achieving the goals and objectives.

- Many propulsion alternatives and choices exist. They provide the means to meet the system performance requirements and the greatest opportunity of reaching the desired mission objectives.

- Recognizing the above, the SPST Functional Requirements Sub-team has drawn on the knowledge, expertise, and experience of their members, to document information (insight) that will effectively aid the "Architectural Concept Developer" in the beginning of the design process to understand the differences between the alternatives.

The propulsion system "choices" with their "pros & cons" are presented in 5-major groups.

1. *System Integration Focused on the requirement for safety reliability, dependability, maintainability and low cost.*
2. *Non Chemical Propulsion*
3. *Chemical Propulsion Propellant and Combustion*
4. *Functional Integration Focused on the many propulsive or closely associated functions and the rocket combustion cycle*
5. *Thermal Management*

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System Integration Approach – Focus on Safety, Reliability, Dependability, Maintainability, and Low Cost

Successful system integration requires a strong systems engineering process & subsystem knowledge-base. The design choice knowledge-base is grouped in 7-areas.

1. Vehicle configuration of propellant tanks (e.g. placement of tanks: parallel, toroidal/nested)
2. Propulsion system engine propellant feed technique (press-fed, pump-fed, electric, reciprocating)
3. Propellant transfer pump location (pump integration w/tanks, w/TCA*, aft-structure)
4. Functionally optimizing propulsion components vs. traditional stand-alone rocket engine (turbopump w/TCA, Separated TPA* & TCA, IVHM & EHMS, Integrated HM)
5. Main rocket engine start considerations (fast, stepped, or soft-steady ramp)
6. Number of main rocket engine nozzles and their placement (vectoring along axis, fixed w/ACS)
7. Structural design of aft end of vehicle (closed base area w/Heat shield, aerodynamically integrated)

*TCA=Thrust Chamber Assembly
TPA=Turbopump Assembly
HMS=Health Management System
ACS=Auxiliary Control System

System Integration Approach – Pros & Cons Example

Architectural Candidate	Propulsion System Choice	Pro's	Con's
System Integration for Safety, Reliability, Dependability, Maintainability, and Low Cost Considerations (Grouping)			
1. Vehicle configuration of propellant tanks	--Tandem, Lox tank forward & fuel tank aft.--	Moves the vehicle CG forward resulting in reduction of performance loss when thrusting through the CG of the vehicle with engines opposing each other. Also provides greater control authority of the vehicle at a given engine gimble angle when in need of steering. However, if engines are mounted on a single plane and thrusting through the CG, the flight attitude angle is less with respect to the vertical axis of the vehicle and again the gimble angles required for control are less with the greater moment arm length.	Requires long Lox propellant feed lines subject to cryogenic geysering and resulting water hammer loads during ground servicing and vehicle pogo in flight, and engine turbo-pump and feed system thermal conditioning for engine start. All three of these conditions require active sub-systems to accommodate, e.g., pogo suppression system, lox anti-geysering system, and a propellant thermal conditioning system. In addition to the above added sub-systems, the servicing process is much longer and requires process control to maintain a safe vehicle, e.g., lox chill-down to remove the sensible heat of the engine mass – turbo-pump to avoid an uncontrolled geyser during loading; a slow fill loading of the feed system to avoid damage of the tank outlet anti-vortex hardware; and possible feed system drain-back conditioning just before engine start. These constraints compromise holdtime flexibility following replenish complete and require active system functioning with fault tolerance to avoid loss of vehicle. A constraint is also placed on the ground lox-servicing system to condition or avoid warm lox temperatures or two-phase flow at the flight vehicle interface at all times. These above added subsystems add considerable hardware, added weight, added non-recurring hardware cost, ground support infrastructure, consumables, considerable maintenance burden/cost and time and sustaining engineering burden/cost. f vehicle propellant tanks carry the load through the base, the el tank will be required to have the strength/mass to support e lox tank resulting in added weight.

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NON-Chemical Propulsion Systems - Attributes & Characteristics

These propulsion systems are optimally designed for "In-space" or "Vacuum Conditions" and are "power limited" instead of "chemical energy limited"

The design choice knowledge-base is grouped into 4- areas with further delineation.

1. Nuclear (fission) energy powered propulsion
   a) Nuclear Core Heats Low MW* Fluid & Expands Flow Supersonically via a Nozzle
   b) Nuclear Core Heats Working Fluid to Drive a Power Conversion Unit for EP* Thruster
   c) Hybrid Nuclear Performs Both of the Above at Different Phases of Mission
2. Solar energy powered propulsion
   a) Typical PVA Drives EP Thruster, Photon-driven Sail, Solar Energy Used Like 1-a Above
3. Propulsion thrusters
   a) Hall Effect Electrostatic, ION, Arc-jet Electrothermal, Resistojet Electrothermal, MPD, Cold-gas
4. Tether powered propulsion
   a) Electrodynamic-based to Drive an EP or Like Mag-sail, Momentum Exchange Propulsion

*MW=Molecular Weight
EP = Electric Propulsion
MPD=MagnetoPlasma Dynamic

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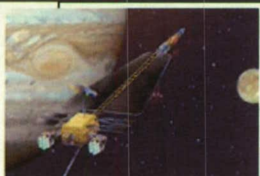
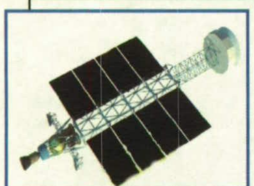
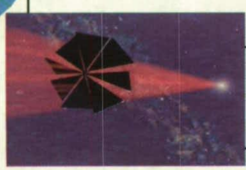
NON-Chemical Propulsion Systems – Pros & Cons Example

Architectural Candidate	Propulsion System Choice	Pro's	Con's
Non-Chemical Propulsion Considerations (Grouping)			
1. Nuclear (Fission) Energy Powered Propulsion			
	Nuclear Thermal Expansion	High performance (Isp) (> 850 sec Isp, Thrust > 1000 lb_f. Provides the high thrust of chemical systems but at 2X the Isp performance. Has less complexity in terms of mechanical systems than Nuclear Electric Propulsion (NEP).	Safety major concern and difficulty to perform the DDT&E (except very small scale below ground level) and to perform the ETO operations. Proven at prototype level only and politically unattractive due to release of fission particles in exhaust.
	Nuclear Electric with Thrusters	Very high performance (Isp) with major increases in payload fraction for planetary orbital, solar system, and possible interstellar missions (Isp 3,000-10,000, Thrust 0.002 to 0.5 lb_f). Planetary trip time decreases compared to all chemical. Potential to eliminate planetary swing-by requirements and increase payload delivery as well as decrease trip time.	No flight experience and many operational unknowns associated with this technology. Additional fluids and complex systems will challenge safety, mission reliability, and cost goals
	Nuclear Bi-Modal with Thrusters	High performance (Isp) coupled with very high NEP Isp. Can deliver high thrust for earth escape with a short thrusting time reducing spiral out trajectory time of NEP. Uses NEP thrusters by using fission reactor as a power source for electric thrusters after planetary escape. Planetary trip time decreases compared to all chemical.	This choice has all the CON's of the two choices above, except the size will allow the DDT&E to be performed underground on earth.
2. Solar Energy Powered Propulsion			
	Solar Electric with Thrusters	Mature technology that is mostly a passive system with high dependability and low cost. Flight proven with Deep Space 1 spacecraft.	Susceptible to space debris causing reduced performance. Limited to low performance/reasonable size. Power available diminishes with $1/R^2$ relative to moving away from Sun.
	Solar Sails	Concept choice is mostly a passive system, but limited to high earth orbit and beyond.	Very large structure and travel speed very slow. No flight experience and low technology maturity. Material strength/density major challenge and plasma sail technology approach maturity even less mature.

Chemical Propulsion Systems - Attributes & Characteristics

These propulsion systems are optimized relative to a synergistic approach within several multi-disciplinary design functions :

Examples : Chemistry, Thermodynamic, Mechanical Design, Materials, Structures, Controls, Performance Analysis

The design choice knowledge-base is grouped into 4- areas.

1. Choice of propellant type
2. Choice of propellant by density or performance considerations
3. Choice of rocket engine combustion chamber/nozzle cooling
4. Mono-propellant vs. bipropellant propulsion system

OXIDIZERS:
*Liquid Oxygen (LOX), O_2
Nitrogen Tetroxide, N_2O_4
Nitrous Oxide, N_2O
Hydrogen Peroxide , H_2O_2
Hydrogen Peroxide (95% Concentration), H_2O_3
*Oxygen Difluoride (FLOX), OF_2
FUELS:
*Liquid Hydrogen, $L(H_2)$
*Methane, CH_4
*Propane, C_3H_8
Kerosene, RP-1
Ethyl Alcohol, C_2H_5OH
Methyl Alcohol, CH_3OH
MonoMethyl Hydrazine, MMH
Hydrazine, N_2H_4
Ammonia, NH_3
Unsymmetrical DiMethyl Hydrazine (UDMH), $(CH_3)_2NNH$
Aniline, $C_6H_5NH_2$
* CRYOGENIC

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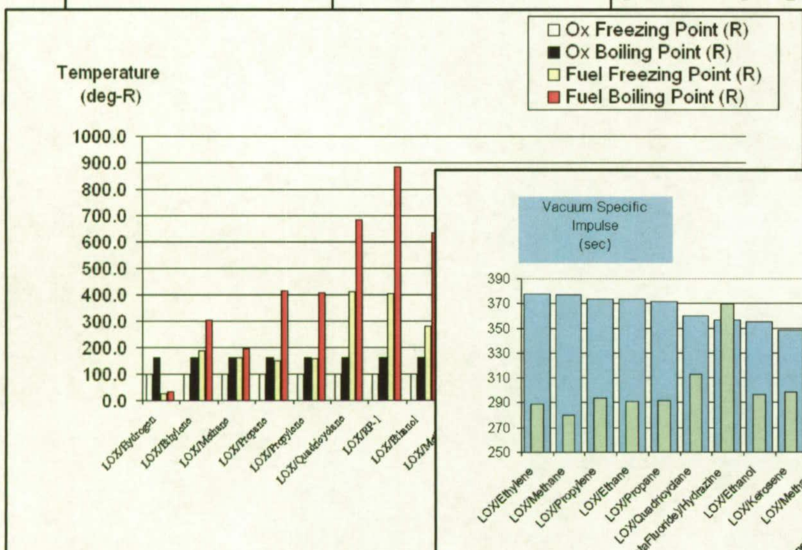
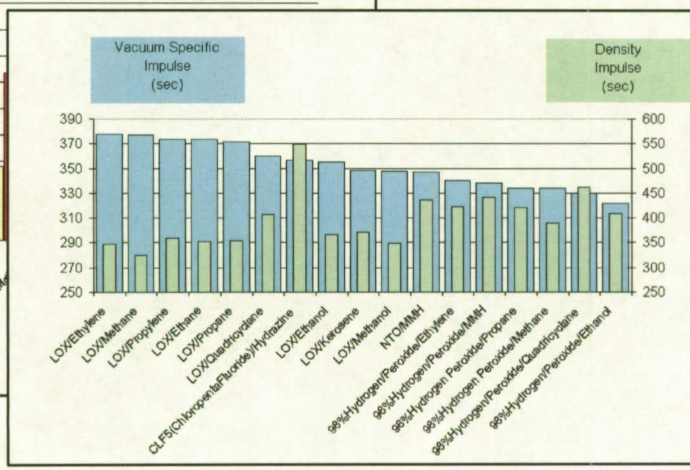
Chemical Propulsion Systems – Pros & Cons Example

Architectural Candidate	Propulsion System Choice	Pro's	Con's
Propellant & Combustion Considerations (Grouping)			
8. Choice of propellant type			
	--All Cryogenic--	Have ~ 40 years experience safely handling NBP propellants in support of servicing and flying launch vehicles. Its mass volume relationship is a function of atmospheric pressure; therefore its flight mass is attained with a fixed passive measuring system. They provide very high performance.	Greatest handling concern for fuels are leaks and potential fires; therefore, requires leak free designs (all welded and avoidance of dynamic seals where ever possible) or very tight process verification practices (verify leak tight). Also LH2 has a very broad flammability and explosive range which requires an operational monitoring and corrective action system to maintain safe operations. Closed compartments are to be avoided by design and if exist must be either pressurized or purged to maintain inert and safe environment. LO2 is impact sensitive with a very small amount of hydrocarbon; therefore, requires all surfaces that it might come in contact to be ultra clean. Proper clothing must be used when handling to avoid cryogenics burns. All small appendages and filters that could contain water vapor or gas contaminants must be removed by purging or evacuation to avoid freezing blockage or chemical contamination. LO2 is of high density and is subject to geysering and water hammer from elevation and dynamics.





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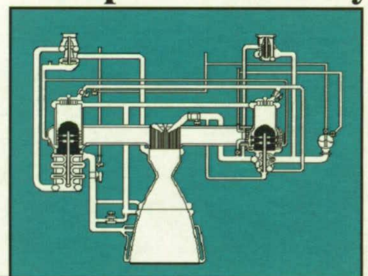
Design Choices Relative to Functional Integration Considerations

The functional integration considerations design choices covers :

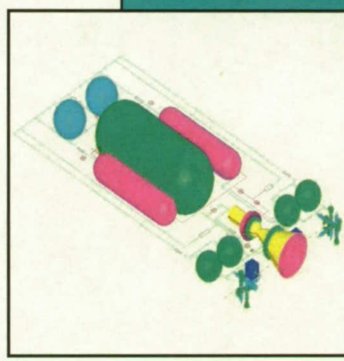
The engine thermodynamic cycles, control approaches for ascent and in-space, and the issues of integrating the sub-systems or trying to couple functionally similar sub-systems together that need to operate concurrently and in isolation.

Example : SSME Cycle



The design choice knowledge-base is grouped into 4- Areas.

1. Rocket combustion cycle choice driven by functional integration
2. Choice of vehicle guidance and control steering (ETO)
3. Choice of vehicle guidance and control steering (In-Space)
4. Integrating propulsion, power, and thermal management functions vs. stand alone



Example : Integrated System

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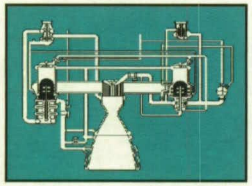
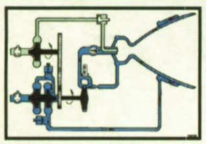
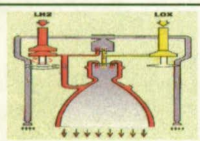
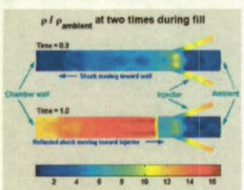
Functional Integration Considerations – Pros & Cons Example

Architectural Candidate	Propulsion System Choice	Pro's	Con's
Functional Integration Considerations (Grouping)			
Rocket combustion cycle choice driven by functional integration			
	-Staged Combustion cycle driven by performance efficiency--	This cycle develops a high efficiency combustion process, but is more complex than the gas generator cycle. The Shuttle SSME uses this cycle; therefore, we have considerable experience with it; however, the maturity of this cycle towards being highly dependable, long life, and low operating cost is very low towards being reusable. The Russian engine technology has use this cycle extensively; however, their application is for only expendables.	The maturity of this cycle towards being highly dependable, long life, and low operating cost is very low. The hardware environments of this cycle are quite extreme making it difficult to achieve a long life and very dependable reusable product, which would accommodate a low cost operation.
	--Expansion cycle driven by long life/dependability--	This choice is inherently robust in comparison to others and the expected dependability would be much higher also. For the above reasons the expected recurring cost would be much lower and the resulting responsiveness of the space transportation system would also be much higher.	This cycle has not been used on a reusable engine and has only been demonstrated in thrust levels suitable for upper stage engines. The scale-up ability of this cycle is limited to creative ways of obtaining the required heat to drive the cycle. Our experience with this cycle is limited to the RL-10 and its derivatives.
	--Gas generator cycle driven by simplicity and size flexibility--	We have a large experience base using this cycle, but the applications were all expendable. This choice is less complex than the combustion cycle and can accommodate a single turbine drive of both propellant pumps reducing the parts count.	This cycle is not as efficient as the combustion cycle. The hardware environments of this cycle are more extreme than the expansion cycle. This makes it difficult to achieve a long life and very dependable reusable product, which would accommodate a low cost operation.
	--Pulse Detonation Combustion--	Less hardware and higher thrust to weight make this choice attractive, but the dynamic demand on the propellant supply valves and the injector environment causes concern for reliability/dependability and long life for the reusable system application.	No flight experience and the dependability/life issues of propellant supply valves and injectors operating in this harsh environment give unknown limitations on reusability application and the resultant life cycle cost. Combustion noise may become a concern with this choice.

Design Choices Relative to Thermal Management Considerations

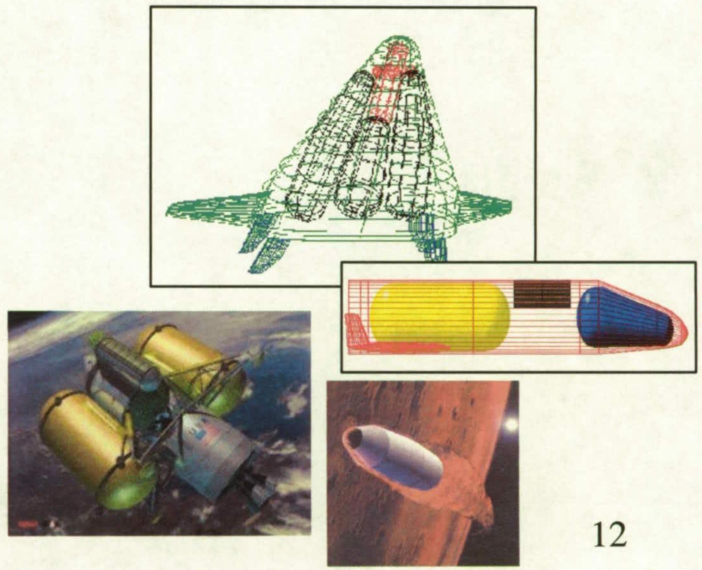
The thermal management considerations basically have been grouped in relationship to :

- The integration or non-integration of the propellant tanks and the "airframe" and how this affects the propellant feed system and the structure

- The methods used for controlling the internal and external thermal environment for cryogenics propellants, reentry heating, gas purging, heat energy recovery and how this affects the propellant feed system and the structure as well as the operability, safety, and cost

The design choice knowledge-base is grouped in 2-Areas.

1. Integral propellant tank and structure vs. tank and aero-shell
2. Cryogenic tank thermo-insulation considerations



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Thermal Management Considerations – Pros & Cons Example

Architectural Candidate	Propulsion System Choice	Pro's	Con's
Thermal Management Consideration (Grouping)			
Integral propellant tank and structure vs. tank and aero-shell			
	--Traditional integral tank/structure--	Main propulsion tank/integral structural choice used on STS, but as an expendable design. This choice eliminates the safety requirement to monitor and control by purge the entrapped areas caused by separate tank and shell design. Therefore this choice eliminates safety systems that results in higher system safety and lower life cycle cost. Results in a lighter overall design solution for increased performance while also resulting in the lowest life cycle cost option.	To support the reusable design approach the tank skin must accommodate the propellant temperatures and the re-entry heating environment. These requirements pose a challenge to the designer when not allowing a purge system to be a part of the solution.
	--Wing tanks/aero shell for vehicle lift--	Would accommodate change out of tanks when needed for the reusable concept. Reduces the sensitivity of balancing the thermal environments of the propellant and the re-entry heating.	Adds requirement for safety monitoring system and safety control systems for both explosive potential and for personnel maintenance when required. Added support systems lower the reliability, safety, and add large ground infrastructure support. These all result in increased life cycle cost. Also this results in the functional verification requirement of thermal insulation parameters between flights. Performance may be less with this choice, as the dry weight will most likely increase.
Cryogenic tank thermo-insulation considerations			
	--Internal tank insulation for cryogenics thermal control and external insulation for re-entry heating structural control--	Provided the design contains margin-robust, this choice provides simple passive approach to a complex design concern. With a minimum quantity of IVHM, this choice should result is a low life cycle solution.	Unless the design technology is very mature, the internal insulation could become an operational nightmare. Have experience with internal insulation for the expendable application (SIV & SIVB stages of Saturn vehicle).
	--Complex purged composite insulation for total heat transfer control--	Designer may produce the lightest weight design? Total insulation external of the structural substrate, which should reduce the need for tank entry.	This choice will require an added flight support system (GHe purge system like Centaur) and its ground support infrastructure driving up the life cycle cost. We have no experience with this choice for reusable applications. IVHM for this concept is also unclear.

SUMMARY

OBJECTIVE OF PRO's & CON's PRODUCT

- To develop a guide to help the "Architectural Concept Developer" in the beginning of the design process to understand the differences between most of the alternatives they would encounter.

CAVEATS

- The Information in the Pro's & Con's table should be evaluated independently and will vary when considered in specific combinations.
- Selection of subsystem elements must be optimized at the systems level using a multi-disciplined Systems Engineering process that permits a focus on multiple attributes and not just performance
- Finally, the Technology Readiness Level and design risk (Cost, Schedule, Safety) must be determined for all design choices !!