Tri-Agency Reliability Engineering Post
Mission Disposal and Extension Assessment Guidance Addendum

1. Introduction

The intent of this addendum to the guidance document, *Tri-Agency Reliability Engineering Guidance: Post Mission Disposal and Extension Assessment,* is to further assist spacefaring entities in assessing their designs and operational plans for extending missions and Post Mission Disposal (PMD) by providing an example. This example assumes a hypothetical mission that has had time on orbit and is now having its probability for 15yrs more of continued/deorbit success updated. Note: the same methods can be used for other scenarios of interest.

Assumptions:

- Star Tracker and GPS receiver are independent of maneuvering systems and each other.
- Payload Components are need for operations but not deorbit; These components cannot impact deorbit operations under nominal or failed conditions.
- Constant/exponential memoryless failure rates are used unless otherwise noted.
- Reliability is assumed to be "Good As New" or 1.0 at time-zero or the start of extension for all systems that are determined to be fully healthy (e.g., without failure history, degradation or wear).

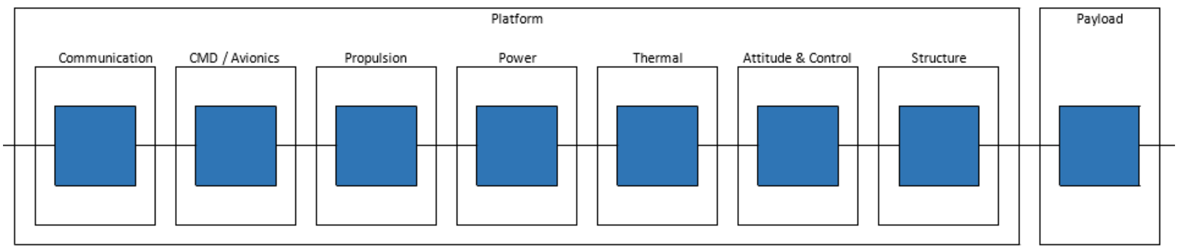
This document is not intended to teach the underlying assumptions and analysis methods or supplant the engagement of reliability engineering.

2. Baseline Extension/Deorbit Example

2.1 Reliability Block Diagram (RBD) Illustration

The Reliability Block Diagram (RBD) methodology describes a system as a number of blocks which are interconnected according to the effect of each block failure on the overall system reliability. As such an RBD is a block diagram that represents the redundancy strategy and not the system functionality. In this example we will be using the satellite system RBD below:

Hypothetical Satellite



$$R_{Hypothetical\ Satellite} = R_{Comm} * R_{Avionics} * R_{Prop} * R_{Power} * R_{Thermal} * R_{ACS} * R_{Struc} * R_{Payload}$$

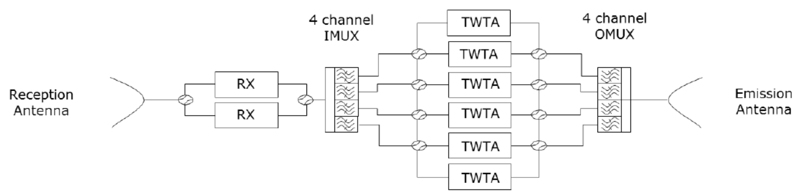
$$R_{Hypothetical\ Satellite} = 0.9602 * R_{Avionics} * R_{Prop} * 0.9807 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.8400$$

$$R_{Hypothetical\ Satellite} = 0.7910 * (R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc})$$

$$For\ 15\ more\ years\ of\ operation$$

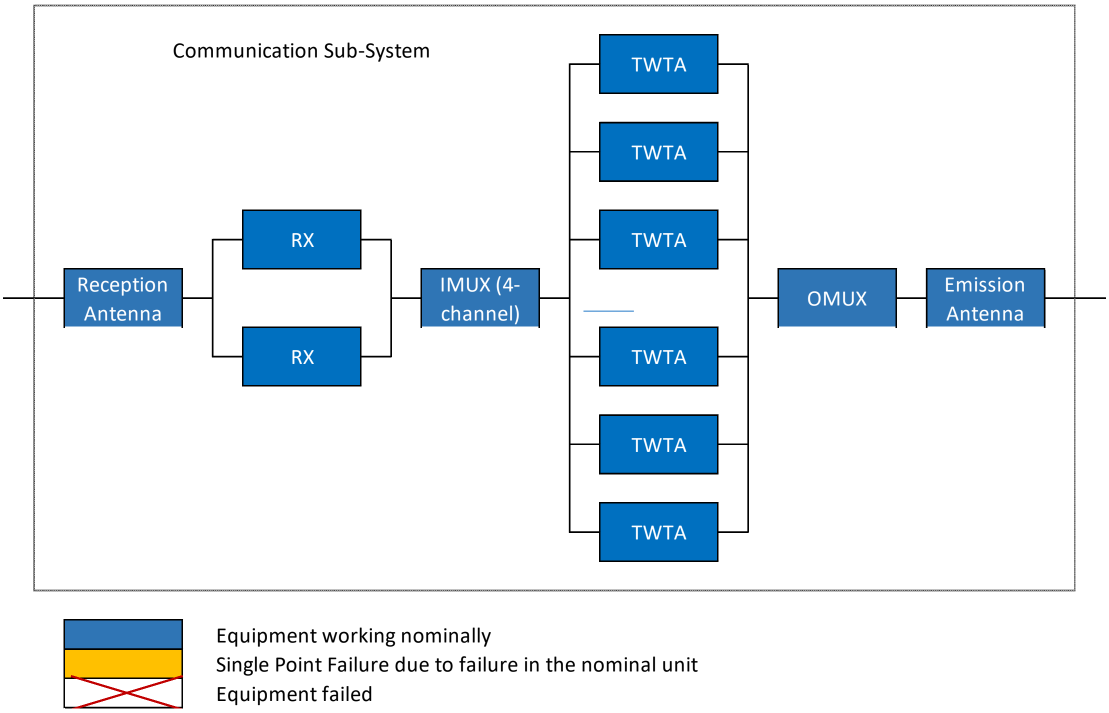
This is based on the supporting subsystem models shown below:

The following Functional model is for the satellite's Communication Subsystem in this example:



Legend:
TWTA: Travelling Wave Tube Assembly
RX: Receiver
IMUX: Input MUltipleXer
OMUX: Output MUltipleXer

and is represented by RBD below for probability estimation. Each item has an attributed Failure In Time (FIT) – number of failures that can occur in one billion (10^9) hours of operation. A constant failure rate is assumed for 15 more years.



Active Redundancy: $\sum_{K=M}^{N} \frac{n!}{k!(n-k)!} * e^{(-\lambda_1 t)}\left(1-e^{-\lambda t}\right)^{n-k} \Rightarrow R_S = 2e^{(-\lambda t)} - e^{(-2\lambda t)}$

Standby Redundancy: $R(t) = e^{(-\lambda t)} * \left(1 + \lambda t + \frac{\lambda^2 t^2}{2!} \ldots \frac{\lambda^{n-1} t^{n-1}}{(n-1)!}\right) \Rightarrow R_S = e^{(-\lambda t)} * (1 + \lambda t)$

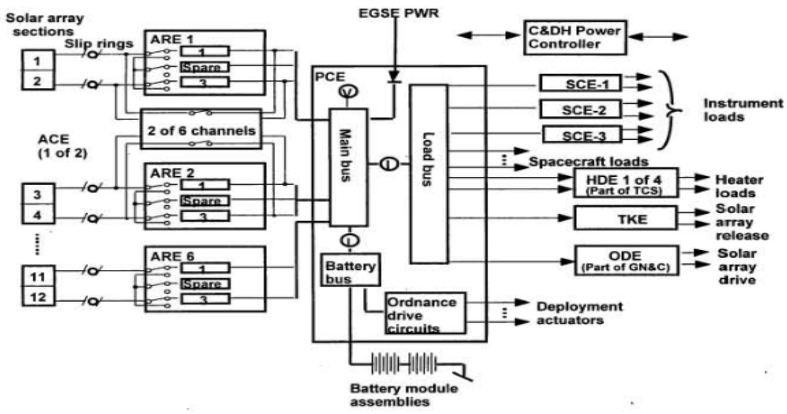
The reliability of the Communication subsystem, is computed based on various factors as per the Table below:

Unit	nb	Active Failure Rate fit	Passive Failure Rate fit	Use ratio (%)	Redundancy				Reliability at years 15
Reception Antenna	1	**10**	1.0	100%	Active	1	/	1	0.999
RX	1	250	25	100%	Active	1		2	0.999
IMUX (4-channel)	1	45	4.5	100%	Active	1		1	0.994
TWTA	1	1000	100	100%	Active	4		6	0.972
OMUX	1	20	2	100%	Active	1		1	0.997
Emission Antenna	1	10	1	100%	Active	1		1	0.999
Communication Sub-System Reliability									**0.96**

Where nb – number of times respective block is considered.

The following Functional Description is for the Hypothetical satellite's Power Subsystem:

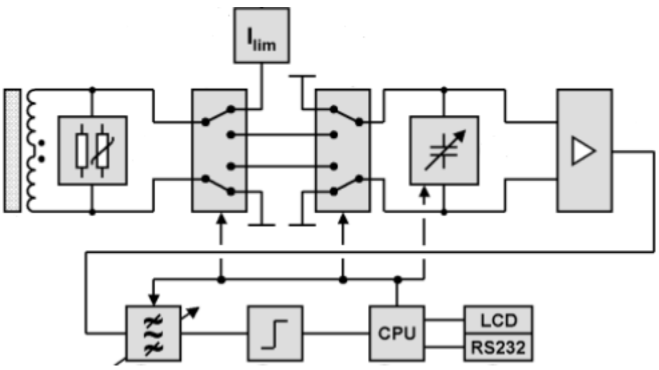
EPS Functional Block Diagram



The reliability of the Power subsystem, is computed as 0.981 for 15 more years, based its various components as per the table below in lieu of an RBD:

		Now	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
59	S/A HOT KNIVES	1	0.999996	0.999993	0.999989	0.999985	0.999982	0.999978	0.999974334	0.999970667	0.999967	0.999963334	0.999959667	0.999956	0.999952	0.999949	0.999945
60	S/A DEPLOYMENT MECH	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
61	TKE	1	0.999997	0.999994	0.999991	0.999988	0.999985	0.9999822	0.999979233	0.999976267	0.9999733	0.999970334	0.999967367	0.999964	0.999961	0.999958	0.999956
62	USO(PART OF CDHS)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
63	S/A HDRS MECH	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.999994	0.999993	0.999992	0.999991	0.99999	0.999989	0.999988	0.999987	0.999986	0.999985
64	ODE(PART OF GNCS)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
65	DDM MOTOR UNIT	1	0.999998	0.999996	0.999994	0.999992	0.99999	0.999988	0.999986	0.999984	0.999982	0.99998	0.999978	0.999976	0.999974	0.999972	0.99997
66	DDM MECHANICAL UNIT	1	1	0.999999	0.999999	0.999999	0.999998	0.999998	0.999997667	0.999997333	0.999997	0.999996667	0.999996333	0.999996	0.999996	0.999995	0.999995
67	S/A STRINGS	1	0.999999	0.999999	0.999998	0.999997	0.999996	0.9999956	0.999994867	0.999994133	0.9999934	0.999992667	0.999991933	0.999991	0.99999	0.99999	0.999989
68	S/A-SADA POWER CONNS	1	0.999905	0.999811	0.999716	0.999622	0.999527	0.999432481	0.999337925	0.999243379	0.999148842	0.999054313	0.998959794	0.998865	0.998771	0.998676	0.998582
69	SLIP-RINGS (PART OF GN&C)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70	ARE	1	0.999999	0.999999	0.999999	0.999998	0.999998	0.999997	0.9999965	0.999996	0.9999955	0.999995	0.9999945	0.999994	0.999994	0.999993	0.999993
71	ACE 1-6(NON-OPERATIONAL)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
72	BATTERY CELLS	1	0.99939	0.99878	0.998171	0.997562	0.996953	0.996344946	0.99573707	0.995129566	0.994522432	0.993915668	0.993309275	0.992703	0.992098	0.991492	0.990887
73	BATTERY CELL HTRS/CONNS	1	0.999994	0.999989	0.999983	0.999977	0.999972	0.9999662	0.999960567	0.999954934	0.999949301	0.999943668	0.999938035	0.999932	0.999927	0.999921	0.999916
74	VCHPS/FCHP/HTRS/CONNS FOR BMA-1	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
75	VCHPS/FCHP/HTRS/CONNS FOR BMA-2	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
76	THERM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
77	THERM CONN	1	1	1	1	1	1	0.9999998	0.999999767	0.999999733	0.9999997	0.999999667	0.999999633	1	1	1	1
78	POWER CONN	1	1	1	1	1	1	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
79	RETURN CONN	1	1	1	1	1	1	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
80	S/C POWER BUS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
81	BUS I/V MON/RC FILTERS	1	0.999998	0.999997	0.999996	0.999994	0.999993	0.999991	0.9999895	0.999988	0.9999865	0.999985	0.9999835	0.999982	0.999981	0.999979	0.999978
82	CTI SLICE	1	0.999987	0.999975	0.999962	0.999949	0.999937	0.999924201	0.999911569	0.999898937	0.999886304	0.999873672	0.99986104	0.999848	0.999836	0.999823	0.999811
83	ORDNANCE SLICE	1	0.999948	0.999896	0.999844	0.999792	0.99974	0.999687624	0.999635571	0.999583521	0.999531473	0.999479428	0.999427386	0.999375	0.999323	0.999271	0.999219
84	SCE-1 +120V BUS/PWR(MODIS)	1	0.999927	0.999854	0.999782	0.999709	0.999636	0.999563048	0.999490241	0.999417439	0.999344643	0.999271852	0.999199067	0.999126	0.999054	0.998981	0.998908
85	SCE-2 +46V BUS/PWR(AMSR)	1	0.999992	0.999983	0.999975	0.999967	0.999959	0.999950201	0.999941901	0.999933601	0.999925302	0.999917002	0.999908703	0.9999	0.999892	0.999884	0.999876
86	SCE-3 PART1 AIRS NB	1	0.999912	0.999825	0.999737	0.999649	0.999561	0.999473669	0.999385974	0.999298287	0.999210608	0.999122936	0.999035272	0.998948	0.99886	0.998772	0.998685
87	SCE-3 PART2 +29V BUS & RELAYS/PWR(ALL INSTS)	1	0.999663	0.999327	0.99899	0.998654	0.998317	0.99798122	0.997645153	0.997309199	0.996973359	0.996637631	0.996302017	0.995967	0.995631	0.995296	0.994961
	EPS SUBSYSTEM	1	0.998705	0.997412	0.996121	0.994831	0.993543	0.992256144	0.990971344	0.989688208	0.988406733	0.987126917	0.985848759	0.984572	0.983297	0.982024	0.980753

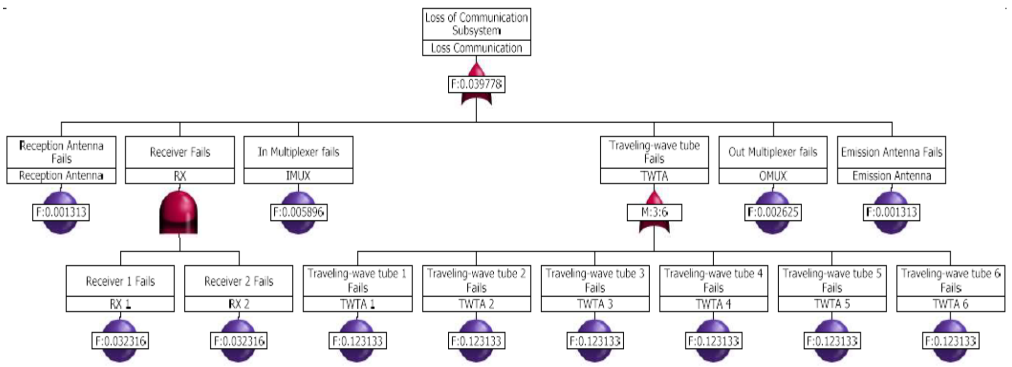
The following is the Functional Description of the satellite's Payload Subsystem in this example:



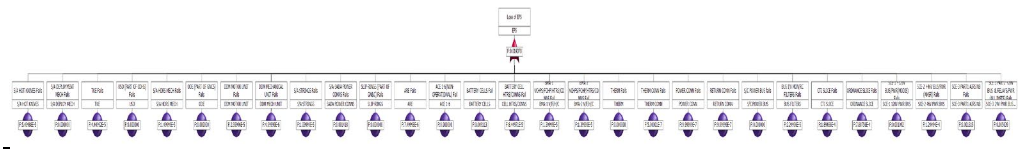
This system is constructed multiple individual electronic parts that is best assessed using parts count catalogue/handbook failure rate estimation or physics of failure. For this example, the payload system is assumed to have the potential for 1.33 failures per million hours or a reliability of 0.84 for 15 more years.

2.2 Fault Tree Illustration

The reliability of the Communication and Electrical Power subsystems, are computed based the same factors shown in the Tables above is evaluate in a fault tree as 0.960 (1-0.039778) and 0.981 (1-0.019934):



Time	Unreliability
0	0.000000
13140.00	0.001170
26280.00	0.002602
39420.00	0.004495
52560.00	0.007004
65700.00	0.010250
78840.00	0.014322
91980.00	0.019281
105120.00	0.025167
118260.00	0.031998
131400.00	0.039778



Time	Unreliability
0	0.000000
8760.00	0.001295
17520.00	0.002590
26280.00	0.003885
35040.00	0.005179
43800.00	0.006472
52560.00	0.007765
61320.00	0.009057
70080.00	0.010349
78840.00	0.011640
87600.00	0.012931
96360.00	0.014221
105120.00	0.015511
113880.00	0.016801
122640.00	0.018089
131400.00	0.019378

Note: It is not effective to construct a Fault Tree for a component that consists of individual electronic parts, therefore a Fault Tree of Payload is not included herein. However, if a system-level FT were completed it would accumulate point estimates like Payload as an undeveloped event and connect subsystem supporting-FTs to the top-level event of system failure (or other event) for extension analysis only since PMD is assumed the Payload is not needed nor can it impact PMD success.

2.3 Probabilistic Risk Assessment (PRA) Illustration

As stated in the introduction, this illustration is limited to finding a 15-year extension to the nominal mission and deorbit at the end of the extension probabilities. Therefore, the example system's PRA scope supplied herein will be limited to PMD only, but this method can be used to evaluate any event sequence of interest within a mission's operational plan.

For disposal, the events assumed are On-Orbit Testing (Spacecraft systems are functionally tested after years of operations to determine current state or $R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)$), Descent (Execution of maneuvers to lower orbital altitude or $R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)$), and Deorbit/Natural Decay (Execution of final maneuver to establish demise orbit $R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr))$ or Execution of aerodynamic-drag-induced demise only), as shown in the PRA master logic diagram below:

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr) = 0.9417 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr + 1500h)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)}$$

$$= \frac{R_{Comm'\ \&\ Power'} * R_{Avionics'} * R_{Prop'} * R_{ACS'-STT'\&\ GPSR'} * R_{STT'\&\ GPSR'} * R_{Struc'}}{0.9417 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}}$$

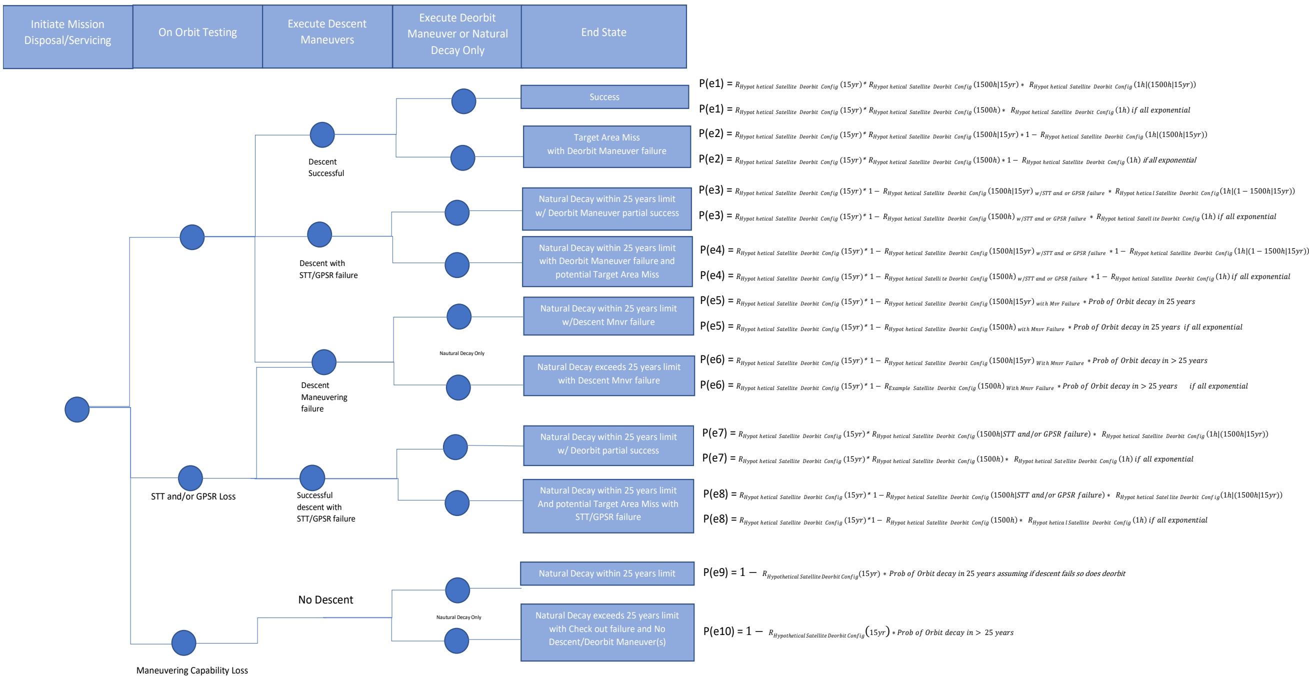
the prime variables indicate values after an additional 1500 hours of use.

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr)) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1hr+1500h|15yr)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$= \frac{R_{Comm"\ \&\ Power"} * R_{Avionic"} * R_{Prop"} * R_{ACS"-STT"\&\ GPSR"} * R_{STT"\&\ GPSR"} * R_{Struc"}}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{\ With\ Mnvr\ Failure\ w/STT\ and\ or\ GPSR\ failure} = R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{\ With\ Mnvr\ Failure}$$

shown with shared event below since maneuvering (Comm/Power/Prop) is not dependent on STT and/or GPSR



Each of the PRA's end-state results (i.e., Disposal Success) shows the collective probability of the sequence of events leading to that state and can be compared to requirements or used to further refine designs/operations.

3. Adjustment Operations/Deorbit Example

3.1 Chi-Squared (CHI2) Adjustment Illustration

The failure rate of an equipment can also be estimated based on field data, providing that sufficient observations are available. One technique commonly used is the CHI2 method. It can be used to refine the design prediction to better characterise the EOL prediction.

For example, we could collect the following data for an item like the TWTA of the Communication subsystem:

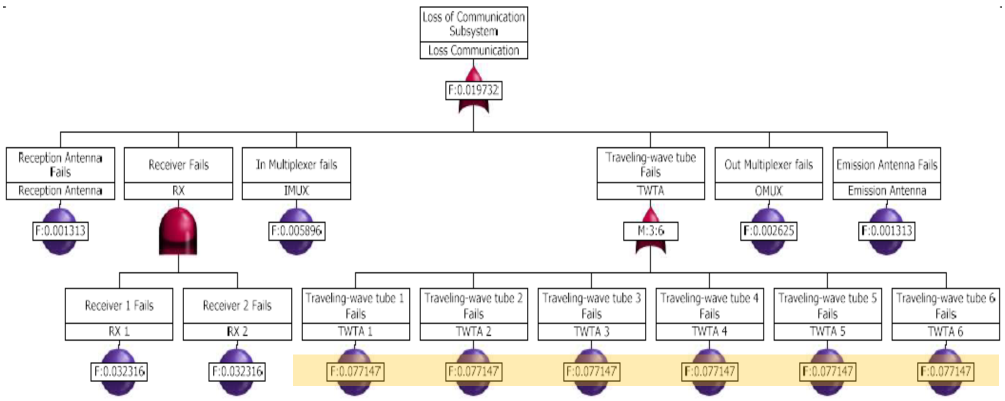
Cumulated operating time of 1500000 hours,
Number of failures observed: none
Confidence level: 60%.

⇨ The measured failure rate is 611 fits.

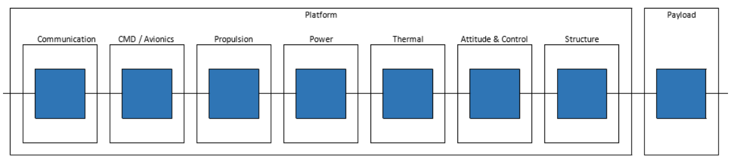
This value of 611 FITs can replace the previous predicted value of 1000 FITs in the RBD shown in section 2 and the Communication Subsystem reliability increases from 0.96 to 0.98 as shown in the following table:

Unit	nb	Active Failure Rate fit	Passive Failure Rate fit	Use ratio (%)	Equivalent Failure Rate	Redundancy				Reliability at years 15.00	Importance
Reception antenna	1	10.00	1.00	100%	10.00	serie				0.998687	6.59%
RX	1	250.00	25.00	100%	250.00	active	1	/	2	0.998956	5.24%
IMUX (4channel)	1	45.00	4.50	100%	45.00	serie				0.994104	29.67%
TWTA	1	611.00	61.10	100%	611.00	active	4	/	6	0.992315	38.71%
OMUX	1	20.00	2.00	100%	20.00	serie				0.997375	13.19%
Emission Antenna	1	10.00	1.00	100%	10.00	serie				0.998687	6.59%
Baseline										**0.98027**	**100.00%**

This value of 611 FITs can also replace the previous predicted value of 1000 FITs in the Communication Fault Tree. The result is that Communication Subsystem failure event decreases from 0.04 to 0.02 or the reliability increases from 0.96022 to 0.98027 and the system reliability calculated here in increases accordingly as well (0.7910 to 0.8076):



Time	Unreliability
0	0.000000
13140.00	0.001137
26280.00	0.002352
39420.00	0.003695
52560.00	0.005212
65700.00	0.006940
78840.00	0.008913
91980.00	0.011157
105120.00	0.013696
118260.00	0.016549
131400.00	0.019732



$$R_{Hypothetical\ Satellite} = 0.9803 * R_{Avionics} * R_{Prop} * 0.9807 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.8400$$

$$R_{Hypothetical\ Satellite} = 0.8076 * (R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc})$$

$$For\ 15\ years\ of\ operation$$

Similarly, this new value of 611 FITs is used to replace previous predicted value in the PRA as follows but the master logic diagram and relationships stay the same as shown below:

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr) = 0.9614 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr + 1500h)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)}$$

$$= \frac{R_{Comm'\&\ Power'} * R_{Avionics'} * R_{Prop'} * R_{ACS'-STT'\&\ GPSR'} * R_{STT'\&\ GPSR'} * R_{Struc'}}{0.9614 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}}$$

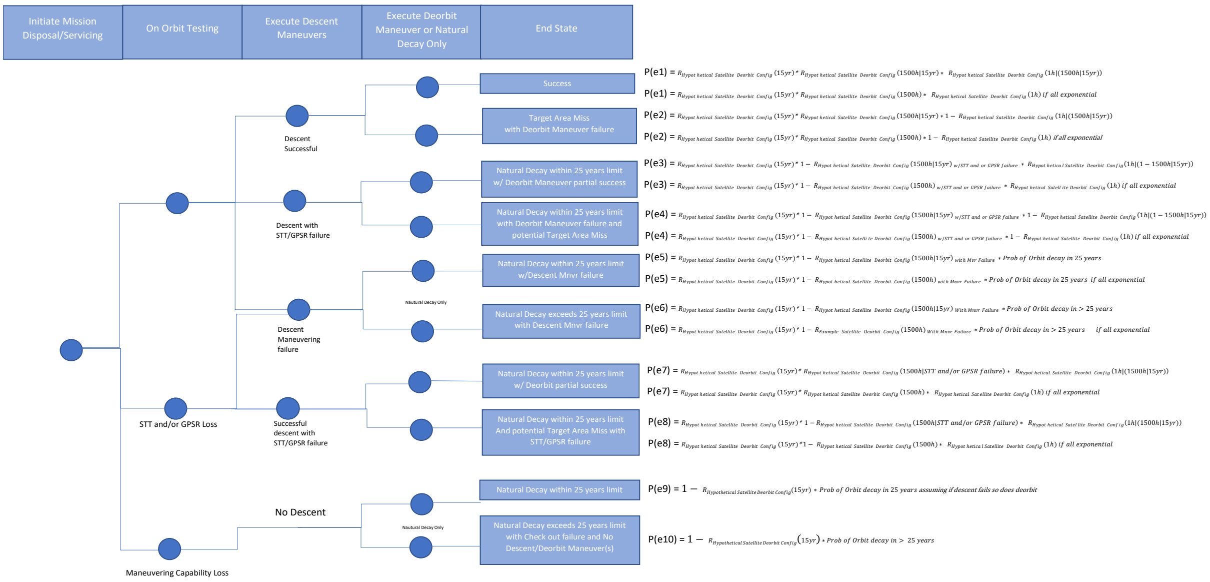
the prime variables indicate values after an additional 1500 hours of use with the new failure rate

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr)) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1hr+1500h|15yr)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$= \frac{R_{Comm''\&\ Power''} * R_{Avionic''} * R_{Prop''} * R_{ACS''-STT''\&\ GPSR''} * R_{STT''\&\ GPSR''} * R_{Struc''}}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure\ w/STT\ and\ or\ GPSR\ failure} = R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure}$$

shown with shared event below since maneuvering (Comm/Power/Prop) is not dependent on STT or GPSR



Each of the PRA's end-state results (i.e., Disposal Success) shows that the collective probability would be impacted by the change and if any system-level fault trees were constructed for these instead these would also be impacted.

3.2 Weibull Adjustment Illustration

The failure rate of an equipment that is aging or wearing can also be estimated based on field data, providing that sufficient observations are available. One technique commonly used is the probability density function (PDF) for a two-parameter Weibull distribution of:

$$f(t) = \theta\beta t^{\beta-1}e^{-\theta t^{\beta}}$$

where t > 0, θ > 0, β > 0. Below is a graph of the probability density as a function of time, *t,* for different values of β and θ. β is the shape parameter. In reliability analysis, θ is the characteristic life, the time when items in a lot will have failed. When β = 1, the Weibull distribution reduces to the exponential distribution.

For example, we could collect the following Solar Array string failure data (16 failures) of the Power subsystem showing wear or aging of the Solar Array on a mission that has been operating for 19+ years already:

ARE	1A	1C	2A	2C	3A	3C	4A	4C	5A	5C	6A	6C
ARM	1	2	3	4	5	6	7	8	9	10	11	12
String 1	Jun-11	Nov-10			Feb-12		Oct-04	Apr-15	Dec-17	May-16	Jul-12	Sep-10
String 2							Sep-09	Feb-18	Nov-18	Jun-16		Oct-11
String 3							Jul-13					Mar-13
String 4							Jul-13					Feb-14
String 5												
String 6												
String 7												
String 8												
String 9												
String 10												
String 11												
PANEL	3	4	5	6	7	8	9	10	11	12	13	14

16 Lost

Lost String
Unconfirmed
Recovered String
* Displays signs of cracked cell

0 Questionable
116 Operational
132 Total Strings

Failures	Date	Hours of Operations Achieved
1	9/23/2009	64824
1	9/3/2010	73104
1	11/7/2010	74664
1	6/28/2011	80256
1	10/20/2011	82992
1	2/4/2012	85560
1	7/19/2012	89544
1	3/1/2013	94944
2	7/18/2013	98280
1	2/2/2014	103056
1	4/26/2015	113808
1	5/3/2016	122760
1	12/27/2017	137232
1	2/22/2018	138600
1	11/21/2018	145128

This data gives us a characteristic life (η) of 456,520 hours, shape (β) of 1.1157 (after modeling iteration), and failure free life (γ) 60,710 hours consistent with this revised closed-form equation:

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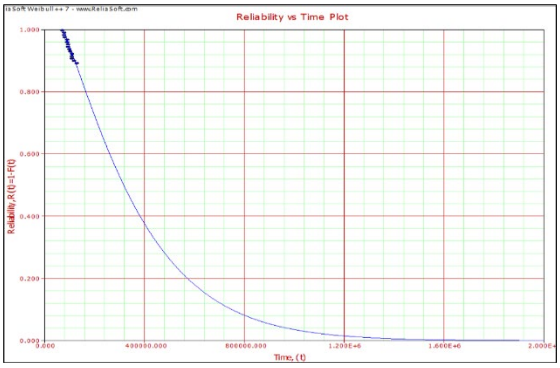
$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

and results in the following values that can be used EOL and PMD predictions with the values below:

Year	P(s) [Weibull]
2019	0.845
2020	0.830
2021	0.815
2022	0.800
2023	0.786
2024	0.771
2025	0.757
2026	0.743
2027	0.729



Given at the end of the extension this Hypothetical satellite requires 69 strings to achieve its mission or execute PMD then using the binomial distribution:

$$F(k;n,p) = \Pr(X \leq k) = \sum_{i=0}^{\lfloor k \rfloor} \binom{n}{i} p^i (1-p)^{n-i}$$

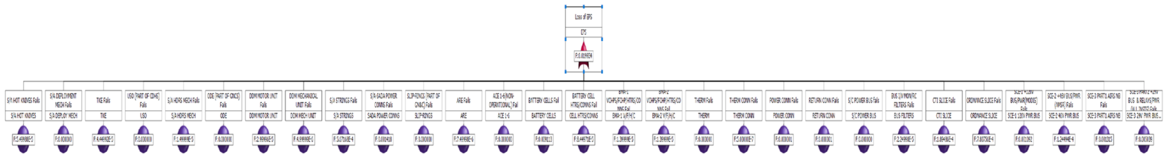
the solar array reliability values moving forward are:

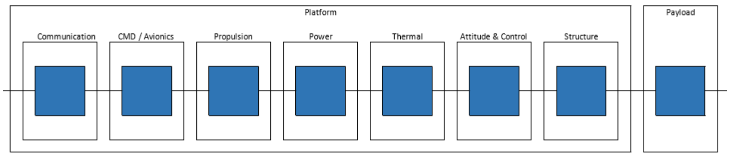
Year	Now	…	+7	+8	+9	+10	+11	+12	+13	+14	+15
Reliability (69 of 132)	1	…	0.999999988	0.999999929	0.999999626	0.999998297	0.99999321	0.999976	0.999924	0.999782	0.999433

These values are then used in the Power Subsystem and reliability decreases from 0.9807 to 0.9802 (15 years from now):

		Now	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
59	S/A HOT KNIVES	1	0.999996	0.999993	0.999989	0.999985	0.999982	0.999978	0.999974334	0.999970667	0.999967	0.999963334	0.999959667	0.999956	0.999952	0.999949	0.999945
60	S/A DEPLOYMENT MECH	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
61	TKE	1	0.999997	0.999994	0.999991	0.999988	0.999985	0.9999822	0.999979233	0.999976267	0.9999733	0.999970334	0.999967367	0.999964	0.999961	0.999958	0.999956
62	USO(PART OF CDHS)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
63	S/A HDRS MECH	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.999994	0.999993	0.999992	0.999991	0.99999	0.999989	0.999988	0.999987	0.999986	0.999985
64	ODE(PART OF GNCS)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
65	DDM MOTOR UNIT	1	0.999998	0.999996	0.999994	0.999992	0.99999	0.999988	0.999986	0.999984	0.999982	0.99998	0.999978	0.999976	0.999974	0.999972	0.99997
66	DDM MECHANICAL UNIT	1	1	0.999999	0.999999	0.999999	0.999998	0.999998	0.999997667	0.999997333	0.999997	0.999996667	0.999996333	0.999996	0.999996	0.999995	0.999995
67	S/A STRINGS	1	1	1	1	1	1	0.999999998	0.999999988	0.999999929	0.999999626	0.999998297	0.99999321	0.999976	0.999924	0.999782	0.999433
68	S/A-SADA POWER CONNS	1	0.999905	0.999811	0.999716	0.999622	0.999527	0.999432481	0.999337925	0.999243379	0.999148842	0.999054313	0.998959794	0.998865	0.998771	0.998676	0.998582
69	SLIP-RINGS (PART OF GN&C)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70	ARE	1	0.999999	0.999999	0.999999	0.999998	0.999998	0.999997	0.9999965	0.999996	0.9999955	0.999995	0.9999945	0.999994	0.999994	0.999993	0.999993
71	ACE 1-6(NON-OPERATIONAL)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
72	BATTERY CELLS	1	0.99939	0.99878	0.998171	0.997562	0.996953	0.996344946	0.99573707	0.995129566	0.994522432	0.993915668	0.993309275	0.992703	0.992098	0.991492	0.990887
73	BATTERY CELL HTRS/CONNS	1	0.999994	0.999989	0.999983	0.999977	0.999972	0.9999662	0.999960567	0.999954934	0.999949301	0.999943668	0.999938035	0.999932	0.999927	0.999921	0.999916
74	VCHPS/FCHP/HTRS/CONNS FOR BMA-1	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
75	VCHPS/FCHP/HTRS/CONNS FOR BMA-2	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
76	THERM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
77	THERM CONN	1	1	1	1	1	1	0.9999998	0.999999767	0.999999733	0.9999997	0.999999667	0.999999633	1	1	1	1
78	POWER CONN	1	1	1	1	1	1	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
79	RETURN CONN	1	1	1	1	1	1	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
80	S/C POWER BUS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
81	BUS I/V MON/RC FILTERS	1	0.999998	0.999997	0.999996	0.999994	0.999993	0.999991	0.9999895	0.999988	0.9999865	0.999985	0.9999835	0.999982	0.999981	0.999979	0.999978
82	CTI SLICE	1	0.999987	0.999975	0.999962	0.999949	0.999937	0.999924201	0.999911569	0.999898937	0.999886304	0.999873672	0.99986104	0.999848	0.999836	0.999823	0.999811
83	ORDNANCE SLICE	1	0.999948	0.999896	0.999844	0.999792	0.99974	0.999687624	0.999635571	0.999583521	0.999531473	0.999479428	0.999427386	0.999375	0.999323	0.999271	0.999219
84	SCE-1 +120V BUS/PWR(MODIS)	1	0.999927	0.999854	0.999782	0.999709	0.999636	0.999563048	0.999490241	0.999417439	0.999344643	0.999271852	0.999199067	0.999126	0.999054	0.998981	0.998908
85	SCE-2 +46V BUS/PWR(AMSR)	1	0.999992	0.999983	0.999975	0.999967	0.999959	0.999950201	0.999941901	0.999933601	0.999925302	0.999917002	0.999908703	0.9999	0.999892	0.999884	0.999876
86	SCE-3 PART1 AIRS NB	1	0.999912	0.999825	0.999737	0.999649	0.999561	0.999473669	0.999385974	0.999298287	0.999210608	0.999122936	0.999035272	0.998948	0.99886	0.998772	0.998685
87	SCE-3 PART2 +29V BUS & RELAYS/PWR(ALL INSTS)	1	0.999663	0.999327	0.99899	0.998654	0.998317	0.99798122	0.997645153	0.997309199	0.996973359	0.996637631	0.996302017	0.995967	0.995631	0.995296	0.994961
	EPS SUBSYSTEM	1	0.998706	0.997413	0.996123	0.994834	0.993546	0.992260508	0.99097642	0.989693944	0.988412887	0.987132476	0.985850017	0.984557	0.983232	0.981821	0.980207

These values can replace the previous predicted values in the Power Fault Tree and the subsystem's failure event increases from 0.019934 to 0.028468 or the reliability decreases from 0.9807 to 0.9802 and the system reliability calculated here in decreases accordingly as well (0.7910 to 0.7906):





$$R_{Hypothetical\ Satellite} = 0.9602 * R_{Avionics} * R_{Prop} * 0.9802 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.8400$$

$$R_{Hypothetical\ Satellite} = 0.7906 * (R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc})$$

$$For\ 15\ more\ years\ of\ operation$$

Similarly, this new value of Power Subsystem prediction of 0.9802 is used to replace previous predicted value in a system FT or the PRA as follows but the master logic diagram and relationships stay the same as shown below:

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr) = 0.9612 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr+1500h)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)}$$

$$= \frac{R_{Comm'\ \&\ Power'} * R_{Avionics'} * R_{Prop'} * R_{ACS'-STT'\&\ GPSR'} * R_{STT'\&\ GPSR'} * R_{Struc'}}{0.9612 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}}$$

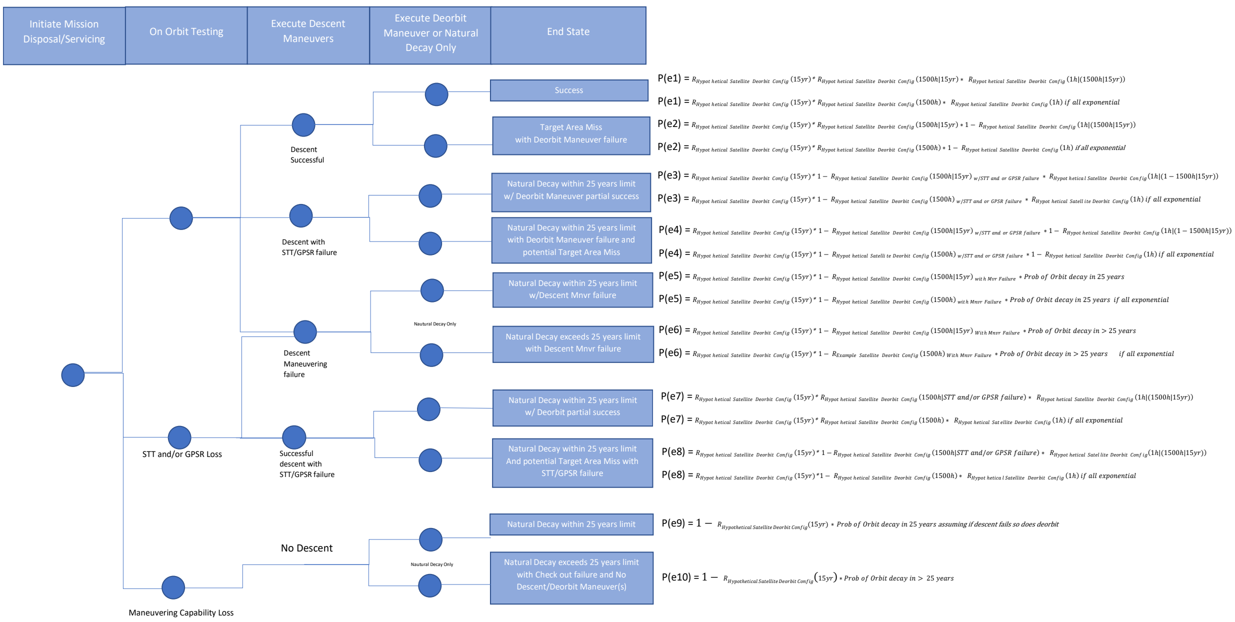
the prime variables indicate values after an additional 1500 hours of use with the new failure rate

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr)) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1hr+1500h|15yr)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$= \frac{R_{Comm''\ \&\ Power''} * R_{Avionic''} * R_{Prop''} * R_{ACS''-STT''\&\ GPSR''} * R_{STT''\&\ GPSR''} * R_{Struc''}}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure\ w/STT\ and\ or\ GPSR\ failure} = R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure}$$

shown with shared event below since maneuvering (Comm/Power/Prop) is not dependent on STT or GPSR



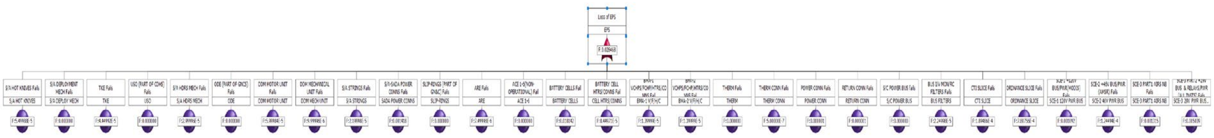
Again, each of the PRA's end-state results (i.e., Disposal Success) shows the collective probability would be impacted by the change.

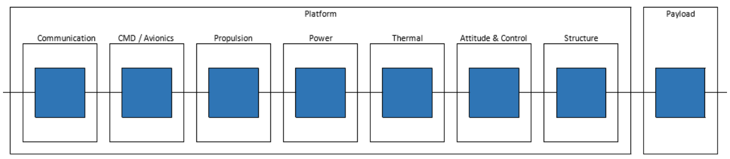
3.3 Engineering Judgement Adjustment Illustration

The failure rate of an equipment that has been operated for some time but is not showing wear can have but is known to be susceptible to aging (e.g., mechanisms, batteries, solar cells for power) its probabilities can be adjusted using accepted engineering judgement. The table below shows, in the neon green rows, the impacts of adjusting the underlying rate by 1.5 x Failure Rate to impute unseen degradation, while a "good-as-new" probability (1.0) is still assumed. Given this adjustment the reliability of the Power subsystem, is computed now computed 0.9717 as versus 0.9807 at 15years.

		Now	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
59	S/A HOT KNIVES	1	0.999996	0.999993	0.999989	0.999985	0.999982	0.999978	0.999974334	0.999970667	0.999967	0.999963334	0.999959667	0.999956	0.999952	0.999949	0.999945
60	S/A DEPLOYMENT MECH	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
61	TKE	1	0.999997	0.999994	0.999991	0.999988	0.999985	0.9999822	0.999979233	0.999976267	0.9999733	0.999970334	0.999967367	0.999964	0.999961	0.999958	0.999956
62	USO(PART OF CDHS)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
63	S/A HDRS MECH	1	0.999998	0.999996	0.999994	0.999992	0.99999	0.999988	0.999986	0.999984	0.999982	0.99998	0.999978	0.999976	0.999974	0.999972	0.99997
64	ODE(PART OF GNCS)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
65	DDM MOTOR UNIT	1	0.999996	0.999992	0.999988	0.999984	0.99998	0.999976	0.999972	0.999968	0.999964001	0.999960001	0.999956001	0.999952	0.999948	0.999944	0.99994
66	DDM MECHANICAL UNIT	1	0.999999	0.999999	0.999998	0.999997	0.999997	0.999996	0.999995333	0.999994667	0.999994	0.999993333	0.999992667	0.999992	0.999991	0.999991	0.99999
67	S/A STRINGS	1	0.999999	0.999997	0.999996	0.999994	0.999993	0.9999912	0.999989733	0.999988267	0.9999868	0.999985333	0.999983867	0.999982	0.999981	0.999979	0.999978
68	S/A-SADA POWER CONNS	1	0.999905	0.999811	0.999716	0.999622	0.999527	0.999432481	0.999337925	0.999243379	0.999148842	0.999054313	0.998959794	0.998865	0.998771	0.998676	0.998582
69	SLIP-RINGS (PART OF GN&C)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70	ARE	1	0.999999	0.999999	0.999999	0.999998	0.999998	0.999997	0.9999965	0.999996	0.9999955	0.999995	0.9999945	0.999994	0.999994	0.999993	0.999993
71	ACE 1-6(NON-OPERATIONAL)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
72	BATTERY CELLS	1	0.99878	0.997562	0.996345	0.99513	0.993916	0.992703251	0.991492313	0.990282853	0.989074867	0.987868356	0.986663315	0.98546	0.984258	0.983057	0.981858
73	BATTERY CELL HTRS/CONNS	1	0.999994	0.999989	0.999983	0.999977	0.999972	0.9999662	0.999960567	0.999954934	0.999949301	0.999943668	0.999938035	0.999932	0.999927	0.999921	0.999916
74	VCHPS/FCHP/HTRS/CONNS FOR BMA-1	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
75	VCHPS/FCHP/HTRS/CONNS FOR BMA-2	1	0.999999	0.999998	0.999997	0.999996	0.999995	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
76	THERM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
77	THERM CONN	1	1	1	1	1	1	0.9999998	0.999999767	0.999999733	0.9999997	0.999999667	0.999999633	1	1	1	1
78	POWER CONN	1	1	1	1	1	1	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
79	RETURN CONN	1	1	1	1	1	1	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
80	S/C POWER BUS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
81	BUS I/V MON/RC FILTERS	1	0.999998	0.999997	0.999996	0.999994	0.999993	0.999991	0.9999895	0.999988	0.9999865	0.999985	0.9999835	0.999982	0.999981	0.999979	0.999978
82	CTI SLICE	1	0.999987	0.999975	0.999962	0.999949	0.999937	0.999924201	0.999911569	0.999898937	0.999886304	0.999873672	0.99986104	0.999848	0.999836	0.999823	0.999811
83	ORDNANCE SLICE	1	0.999948	0.999896	0.999844	0.999792	0.99974	0.999687624	0.999635571	0.999583521	0.999531473	0.999479428	0.999427386	0.999375	0.999323	0.999271	0.999219
84	SCE-1 +120V BUS/PWR(MODIS)	1	0.999927	0.999854	0.999782	0.999709	0.999636	0.999563048	0.999490241	0.999417439	0.999344643	0.999271852	0.999199067	0.999126	0.999054	0.998981	0.998908
85	SCE-2 +46V BUS/PWR(AMSR)	1	0.999992	0.999983	0.999975	0.999967	0.999959	0.999950201	0.999941901	0.999933601	0.999925302	0.999917002	0.999908703	0.9999	0.999892	0.999884	0.999876
86	SCE-3 PART1 AIRS NB	1	0.999912	0.999825	0.999737	0.999649	0.999561	0.999473669	0.999385974	0.999298287	0.999210608	0.999122936	0.999035272	0.998948	0.99886	0.998772	0.998685
87	SCE-3 PART2 +29V BUS & RELAYS/PWR(ALL INSTS)	1	0.999663	0.999327	0.99899	0.998654	0.998317	0.99798122	0.997645153	0.997309199	0.996973359	0.996637631	0.996302017	0.995967	0.995631	0.995296	0.994961
	EPS SUBSYSTEM	1	0.998092	0.996187	0.994286	0.992389	0.990495	0.988605272	0.986718814	0.984835956	0.982956691	0.981081011	0.979208911	0.97734	0.975475	0.973614	0.971756

These values can replace the previous predicted values in the Power Fault Tree and the subsystem's failure event increases from 0.019934 to 0.028468 or the reliability decreases from 0.9807 to 0.9715 and the system reliability calculated here in decreases accordingly as well (0.7910 to 0.7836):





$$R_{Hypothetical\ Satellite} = 0.9602 * R_{Avionics} * R_{Prop} * 0.9715 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.8400$$

$$R_{Hypothetical\ Satellite} = 0.7836 * \left(R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc}\right)$$

$$For\ 15\ more\ years\ of\ continued\ operation$$

Similarly, this new value of Power Subsystem prediction of 0.9715 is used to replace previous predicted value in the PRA as follows but the master logic diagram and relationships stay the same as shown below:

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr) = 0.9328 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr + 1500h)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)}$$

$$= \frac{R_{Comm'\&\ Power'} * R_{Avionics'} * R_{Prop'} * R_{ACS'-STT'\&\ GPSR'} * R_{STT'\&\ GPSR'} * R_{Struc'}}{0.9328 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}}$$

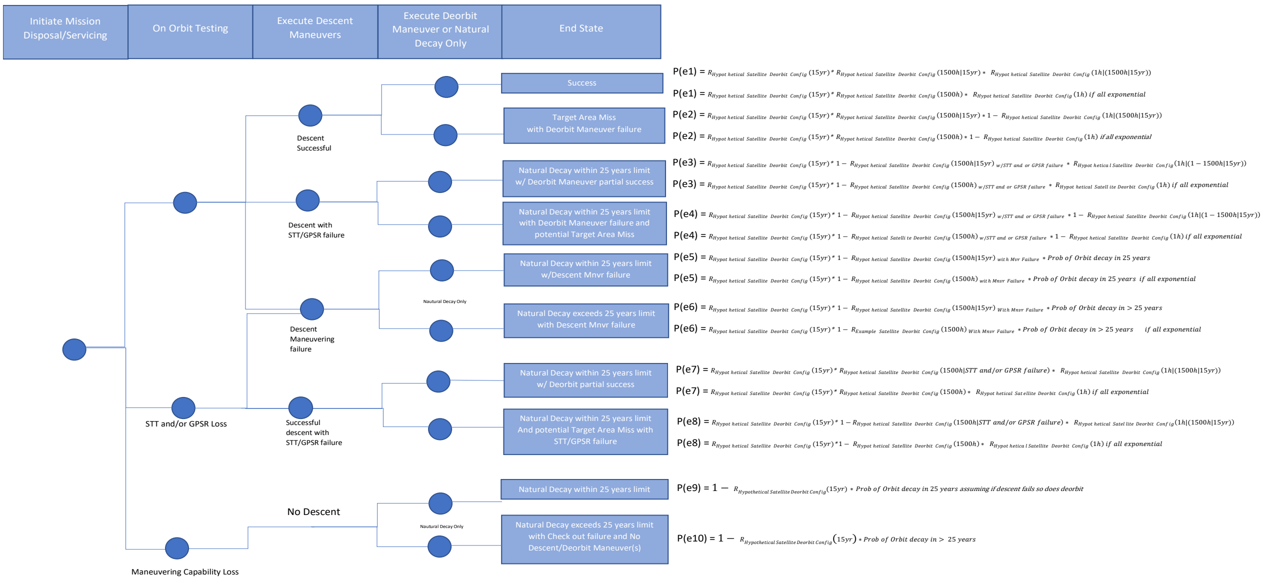
the prime variables indicate values after an additional 1500 hours of use with the new failure rate

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr)) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1hr+1500h|15yr)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$= \frac{R_{Comm"\&Power"} * R_{Avionic"} * R_{Prop"} * R_{ACS"-STT"\&GPSR"} * R_{STT"\&GPSR"} * R_{Struc"}}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure\ w/STT\ and\ or\ GPSR\ failure} = R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure}$$

shown with shared event below since maneuvering (Comm/Power/Prop) is not dependent on STT or GPSR



Once more, each of the PRA's end-state results (i.e., Disposal Success) shows the collective probability would be impacted by the changes and if any system-level fault trees were constructed for these instead these would also be impacted.

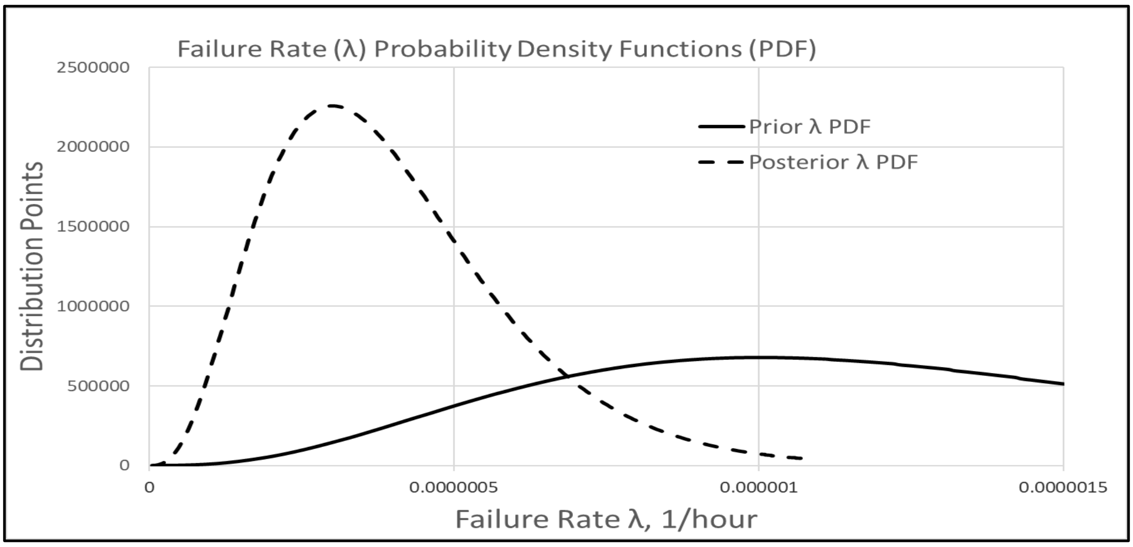
3.4 Bayesian Adjustment Illustration

The classical statistical method of Bayesian Inference can also be used to adjust or recalculate underlying failure rates. This method is best used when there are components for which the on-orbit/test failure data is insufficient to calculate a new failure rate; however, there is enough success and failure on-orbit/test data from other mission to consider updating the existing failure rate assumed. This method can be used prior to design, prior to operations, or in-situ and learns from data incrementally until convergence on a new failure rate is reached.

For instance, the payload in the example system could have an on-orbit performance history on similar missions of $7{,}127{,}352$ hrs and no failures ($r = 0$). This data would enable the Bayes' estimation of the failure rate λ, as follows assuming a gamma prior and using these values, expert estimate of the relative error (uncertainty) of λ was assumed to be 50%, which is equivalent to CoV(λ) = 0.5, and $E(\lambda) = 1.33\ x\ 10^{-6}$ $(see\ Section\ 1.1)$:

- $\delta = \frac{1}{[CoV(\lambda)]^2} = 4$
- $E(\lambda) = 1.33\ x\ 10^{-6}[Parts\ Count\ Failure\ Rate].$
- $\rho = \frac{\delta}{E(\lambda)} = 3.01\ x10^{6}\ \ hours$
- $T = 7{,}127{,}352\ hrs\ \ and\ the\ number\ of\ failures\ r\ = \ 0$

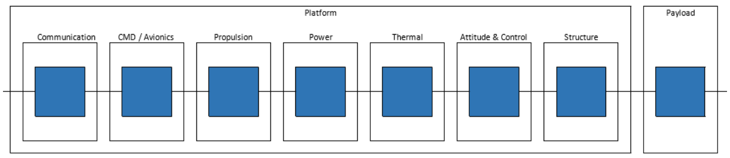
$$\lambda_{Bayesian} = \frac{\delta'}{\rho'} = \frac{\delta+r}{\rho+T} = 3.95x10^{-7}\left(\frac{1}{hours}\right).$$



Prior and posterior PDFs of the payload failure rate

Once a posterior is attained it should be routinely updated so its distribution (most precise if used) or a selected point estimate (i.e., mean) can be used for the component in further system assessment along with the good-as-new assumption. While this example shows one prior-posterior assumption set, any prior and distribution type (e.g., binomial for failures in n demands, Poisson for events in time, gamma for n failure in time) can be used with enough data and will converge on the same posterior distribution.

Given this newly derived payload failure rate the reliability of the Payload subsystem, is computed now computed 0.9494 as versus 0.84 at 15 years and impact the system reliability calculated here RBD and FT (0.7910 to 0.8940):



$$R_{Hypothetical\ Satellite} = 0.9602 * R_{Avionics} * R_{Prop} * 0.9807 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.9494$$

$$R_{Hypothetical\ Satellite} = 0.8940 * \left(R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc}\right)$$

$$For\ 15\ more\ years\ of\ operation$$

While a system level FT or payload-scenario PRA would be impacted by this change, the PMD PRA would remain unchanged since PMD doesn't require the payload.

3.5 Collective Adjustment Illustration

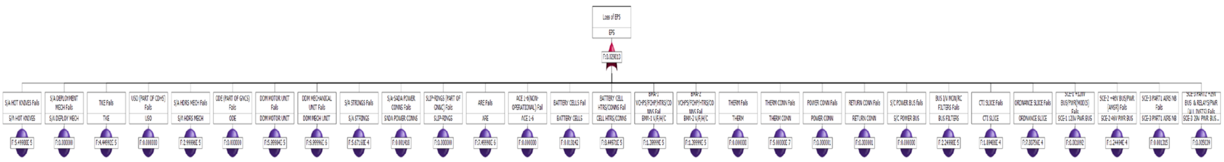
It should be noted that <u>any</u> adjustment does not exclude another adjustment within the same or adjacent subsystems or components or systems. For example, the Power Subsystem could have both components that are susceptible to wear (neon green lines) that do not exhibit wear-symptoms and those that exhibit symptoms (blue numbers). In each case these elements would have the appropriate adjustments applied Weibull for the solar array strings (see section 3.2) and engineering judgement for the others (See section 3.3).

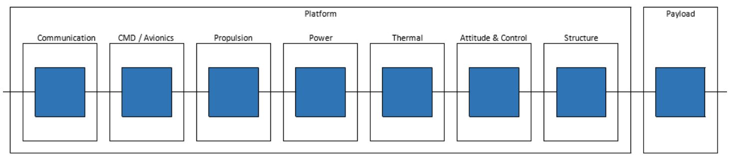
Given these adjustments the reliability of the Power subsystem, is computed now computed 0.9712 as versus the nominal 0.9807 (or Engineering Adjustment only value of 0.9717) at 15years.

		Now	1	2	3	4	5
59	S/A HOT KNIVES	1	0.999996	0.999993	0.999989	0.999985	0.999982
60	S/A DEPLOYMENT MECH	1	1	1	1	1	1
61	TKE	1	0.999997	0.999994	0.999991	0.999988	0.999985
62	USO(PART OF CDHS)	1	1	1	1	1	1
63	S/A HDRS MECH	1	0.999998	0.999996	0.999994	0.999992	0.99999
64	ODE(PART OF GNCS)	1	1	1	1	1	1
65	DDM MOTOR UNIT	1	0.999996	0.999992	0.999988	0.999984	0.99998
66	DDM MECHANICAL UNIT	1	0.999999	0.999999	0.999998	0.999997	0.999997
67	S/A STRINGS	1	1	1	1	1	1
68	S/A-SADA POWER CONNS	1	0.999905	0.999811	0.999716	0.999622	0.999527
69	SLIP-RINGS (PART OF GN&C)	1	1	1	1	1	1
70	ARE	1	0.999999	0.999999	0.999999	0.999998	0.999998
71	ACE 1-6(NON-OPERATIONAL)	1	1	1	1	1	1
72	BATTERY CELLS	1	0.99878	0.997562	0.996345	0.99513	0.993916
73	BATTERY CELL HTRS/CONNS	1	0.999994	0.999989	0.999983	0.999977	0.999972
74	VCHPS/FCHP/HTRS/CONNS FOR BMA-1	1	0.999999	0.999998	0.999997	0.999996	0.999995
75	VCHPS/FCHP/HTRS/CONNS FOR BMA-2	1	0.999999	0.999998	0.999997	0.999996	0.999995
76	THERM	1	1	1	1	1	1
77	THERM CONN	1	1	1	1	1	1
78	POWER CONN	1	1	1	1	1	1
79	RETURN CONN	1	1	1	1	1	1
80	S/C POWER BUS	1	1	1	1	1	1
81	BUS I/V MON/RC FILTERS	1	0.999998	0.999997	0.999996	0.999994	0.999993
82	CTI SLICE	1	0.999987	0.999975	0.999962	0.999949	0.999937
83	ORDNANCE SLICE	1	0.999948	0.999896	0.999844	0.999792	0.99974
84	SCE-1 +120V BUS/PWR(MODIS)	1	0.999927	0.999854	0.999782	0.999709	0.999636
85	SCE-2 +46V BUS/PWR(AMSR)	1	0.999992	0.999983	0.999975	0.999967	0.999959
86	SCE-3 PART1 AIRS NB	1	0.999912	0.999825	0.999737	0.999649	0.999561
87	SCE-3 PART2 +29V BUS & RELAYS/PWR(ALL INSTS)	1	0.999663	0.999327	0.99899	0.998654	0.998317
	EPS SUBSYSTEM	1	0.998093	0.99619	0.994291	0.992395	0.990503

		6	7	8	9	10	11	12	13	14	15
59	S/A HOT KNIVES	0.999978	0.999974334	0.999970667	0.999967	0.999963334	0.999959667	0.999956	0.999952	0.999949	0.999945
60	S/A DEPLOYMENT MECH	1	1	1	1	1	1	1	1	1	1
61	TKE	0.9999822	0.999979233	0.999976267	0.9999733	0.999970334	0.999967367	0.999964	0.999961	0.999958	0.999956
62	USO(PART OF CDHS)	1	1	1	1	1	1	1	1	1	1
63	S/A HDRS MECH	0.999988	0.999986	0.999984	0.999982	0.99998	0.999978	0.999976	0.999974	0.999972	0.99997
64	ODE(PART OF GNCS)	1	1	1	1	1	1	1	1	1	1
65	DDM MOTOR UNIT	0.999976	0.999972	0.999968	0.999964001	0.999960001	0.999956001	0.999952	0.999948	0.999944	0.99994
66	DDM MECHANICAL UNIT	0.999996	0.999995333	0.999994667	0.999994	0.999993333	0.999992667	0.999992	0.999991	0.999991	0.99999
67	S/A STRINGS	0.999999998	0.999999988	0.999999929	0.999999626	0.999998297	0.99999321	0.999976	0.999924	0.999782	0.999433
68	S/A-SADA POWER CONNS	0.999432481	0.999337925	0.999243379	0.999148842	0.999054313	0.998959794	0.998865	0.998771	0.998676	0.998582
69	SLIP-RINGS (PART OF GN&C)	1	1	1	1	1	1	1	1	1	1
70	ARE	0.999997	0.9999965	0.999996	0.9999955	0.999995	0.9999945	0.999994	0.999994	0.999993	0.999993
71	ACE 1-6(NON-OPERATIONAL)	1	1	1	1	1	1	1	1	1	1
72	BATTERY CELLS	0.992703251	0.991492313	0.990282853	0.989074867	0.987868356	0.986663315	0.98546	0.984258	0.983057	0.981858
73	BATTERY CELL HTRS/CONNS	0.9999662	0.999960567	0.999954934	0.999949301	0.999943668	0.999938035	0.999932	0.999927	0.999921	0.999916
74	VCHPS/FCHP/HTRS/CONNS FOR BMA-1	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
75	VCHPS/FCHP/HTRS/CONNS FOR BMA-2	0.9999944	0.999993467	0.999992533	0.9999916	0.999990667	0.999989733	0.999989	0.999988	0.999987	0.999986
76	THERM	1	1	1	1	1	1	1	1	1	1
77	THERM CONN	0.9999998	0.999999767	0.999999733	0.9999997	0.999999667	0.999999633	1	1	1	1
78	POWER CONN	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
79	RETURN CONN	0.9999996	0.999999533	0.999999467	0.9999994	0.999999333	0.999999267	0.999999	0.999999	0.999999	0.999999
80	S/C POWER BUS	1	1	1	1	1	1	1	1	1	1
81	BUS I/V MON/RC FILTERS	0.999991	0.9999895	0.999988	0.9999865	0.999985	0.9999835	0.999982	0.999981	0.999979	0.999978
82	CTI SLICE	0.999924201	0.999911569	0.999898937	0.999886304	0.999873672	0.99986104	0.999848	0.999836	0.999823	0.999811
83	ORDNANCE SLICE	0.999687624	0.999635571	0.999583521	0.999531473	0.999479428	0.999427386	0.999375	0.999323	0.999271	0.999219
84	SCE-1 +120V BUS/PWR(MODIS)	0.999563048	0.999490241	0.999417439	0.999344643	0.999271852	0.999199067	0.999126	0.999054	0.998981	0.998908
85	SCE-2 +46V BUS/PWR(AMSR)	0.999950201	0.999941901	0.999933601	0.999925302	0.999917002	0.999908703	0.9999	0.999892	0.999884	0.999876
86	SCE-3 PART1 AIRS NB	0.999473669	0.999385974	0.999298287	0.999210608	0.999122936	0.999035272	0.998948	0.99886	0.998772	0.998685
87	SCE-3 PART2 +29V BUS & RELAYS/PWR(ALL INSTS)	0.99798122	0.997645153	0.997309199	0.996973359	0.996637631	0.996302017	0.995967	0.995631	0.995296	0.994961
	EPS SUBSYSTEM	0.98861397	0.986728933	0.984847441	0.982969298	0.98109373	0.97921806	0.977334	0.97542	0.973422	0.971226

These values can replace the previous predicted values in the Power Fault Tree and the subsystem's failure event increases from 0.019934 to 0.029013 or the reliability decreases from 0.9807 to 0.9712:





$$R_{Hypothetical\ Satellite} = 0.9602 * R_{Avionics} * R_{Prop} * 0.9712 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.8400$$

$$R_{Hypothetical\ Satellite} = 0.7833 * (R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc})$$

$$For\ 15\ more\ years\ of\ continued\ operation$$

Similarly, this new value of Power Subsystem is used to replace previous predicted value in a system FT, or the PRA as follows but the master logic diagram and relationships stay the same as shown below:

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr) = 0.9325 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr + 1500h)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)}$$

$$= \frac{R_{Comm'\ \&\ Power'} * R_{Avionics'} * R_{Prop'} * R_{ACS'-STT'\&\ GPSR'} * R_{STT'\&\ GPSR'} * R_{Struc'}}{0.9325 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}}$$

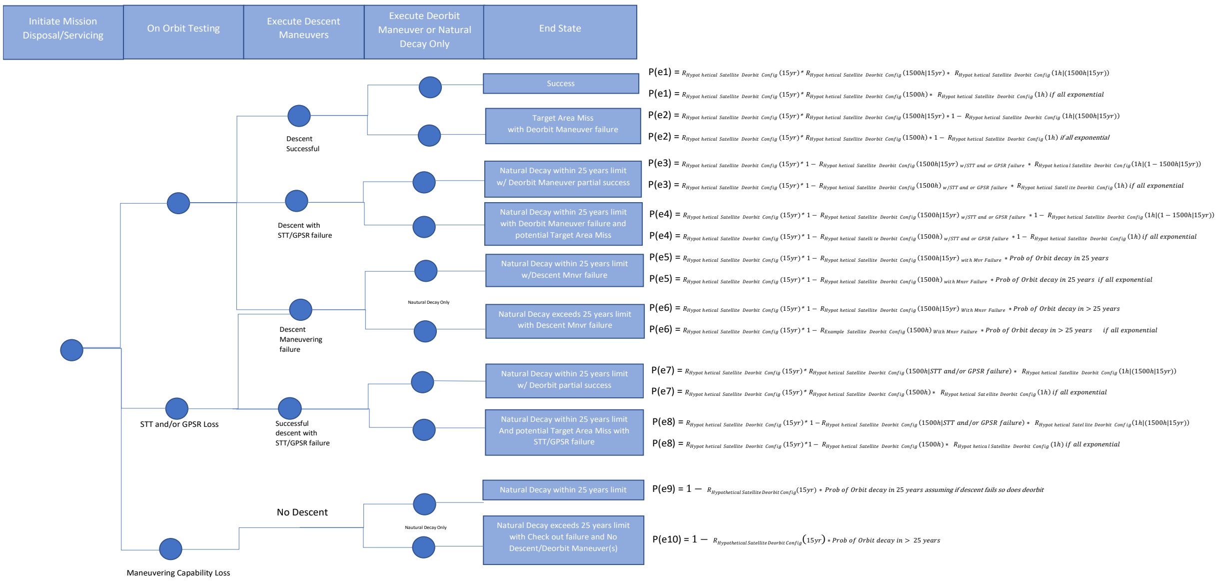
the prime variables indicate values after an additional 1500 hours of use with the new failure rate

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr)) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1hr+1500h|15yr)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

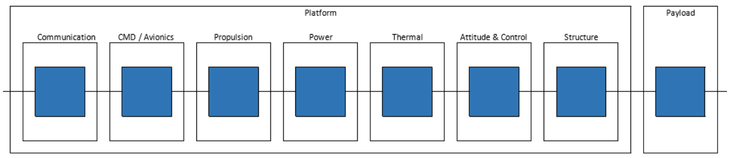
$$= \frac{R_{Comm''\ \&\ Power''} * R_{Avionic''} * R_{Prop''} * R_{ACS''-STT''\&\ GPSR''} * R_{STT''\&\ GPSR''} * R_{Struc''}}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure\ w/STT\ and\ or\ GPSR\ failure} = R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure}$$

shown with shared event below since maneuvering (Comm/Power/Prop) is not dependent on STT and/or GPSR



Further, if all adjustments, cumulative Power (shown above), Communications (shown in section 3.1), and Payload (shown in section 3.4) are applied to the system RBD, FT and PRA the following results are attained:



$$R_{Hypothetical\ Satellite} = 0.9803 * R_{Avionics} * R_{Prop} * 0.9712 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.9494$$

$$R_{Hypothetical\ Satellite} = 0.9039 * (R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc})$$

$$For\ 15\ more\ years\ of\ operation$$

While a system level FT or payload-scenario PRA would be impacted by all these changes, the PMD PRA would be impacted by only the power and communications subsystem changes since PMD doesn't require the payload as shown below:

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr) = 0.9521 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr + 1500h)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)}$$

$$= \frac{R_{Comm'\ \&\ Power'} * R_{Avionics'} * R_{Prop'} * R_{ACS'-STT'\&\ GPSR'} * R_{STT'\&\ GPSR'} * R_{Struc'}}{0.9521 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}}$$

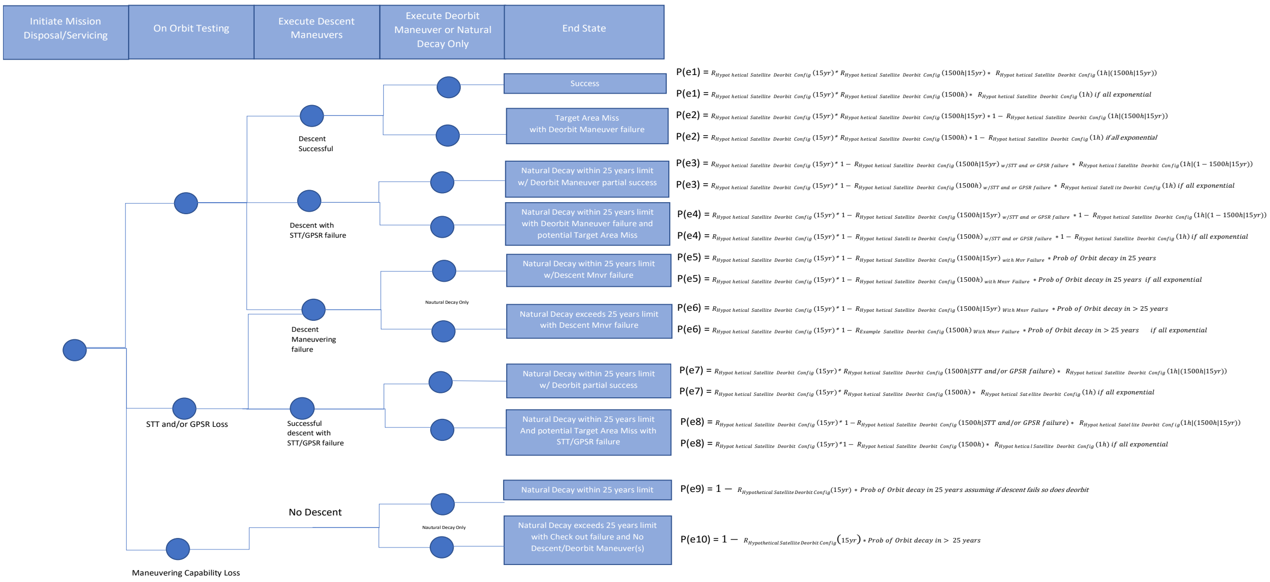
the prime variables indicate values after an additional 1500 hours of use with the new failure rate

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr)) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1hr+1500h|15yr)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$= \frac{R_{Comm''\ \&\ Power''} * R_{Avionic''} * R_{Prop''} * R_{ACS''-STT''\&\ GPSR''} * R_{STT''\&\ GPSR''} * R_{Struc''}}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

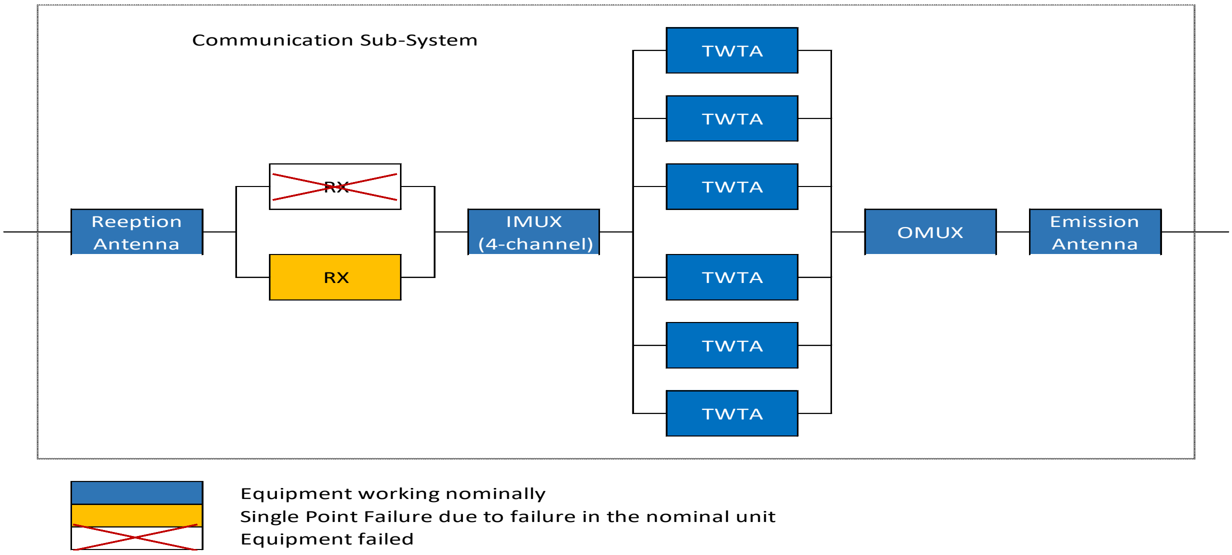
$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure\ w/STT\ and\ or\ GPSR\ failure} = R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure}$$

shown with shared event below since maneuvering (Comm/Power/Prop) is not dependent on STT and/or GPSR



3.6 Failure Adjustment Illustration

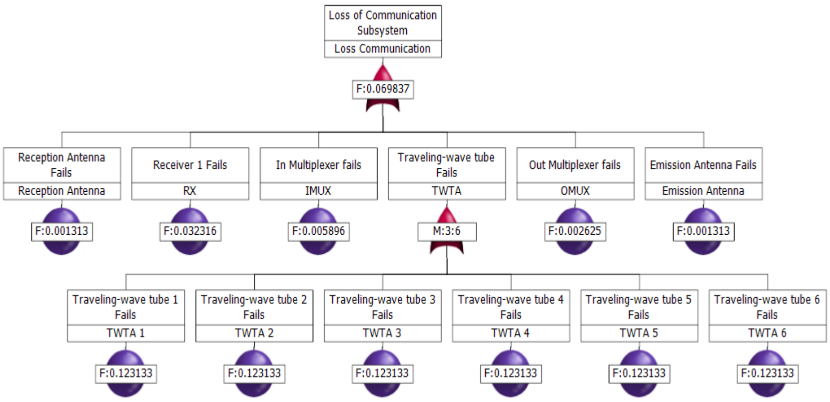
If the hypothetical spacecraft is not fully functional when an extension is considered the failed items should be removed from the RBD/FTA/PRA, as applicable, in addition to any or all cumulative adjustments. For example, if one of the two redundant receivers (Rx) failed in the Communications subsystem, the RBD would be adjusted for the loss of redundancy as shown below:



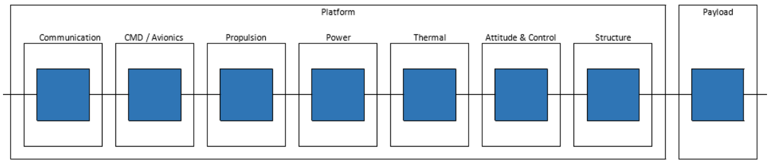
Unit	nb	Active Failure Rate fit	Passive Failure Rate fit	Use ratio (%)	Redundancy				Reliability w/15 more yrs of Ops
Reception Antenna	1	**10**	1.0	100%	Active	1	/	1	0.999
RX	1	250	25	100%	Active	1		1	0.968
IMUX (4-channel)	1	45	4.5	100%	Active	1		1	0.994
TWTA	1	1000	100	100%	Active	4		6	0.972
OMUX	1	20	2	100%	Active	1		1	0.997
Emission Antenna	1	10	1	100%	Active	1		1	0.999
Communication Sub-System Reliability									**0.93**

Further, if this failed system adjustment is applied to the Communications FT and system RBD and PRA (and system FT if developed) the following results are attained:

For 15 more years of operation with only failure adjustment



Time	Unreliability
0	0.000000
13140.00	0.004435
26280.00	0.009091
39420.00	0.014163
52560.00	0.019800
65700.00	0.026116
78840.00	0.033191
91980.00	0.041080
105120.00	0.049813
118260.00	0.059400
131400.00	0.069837

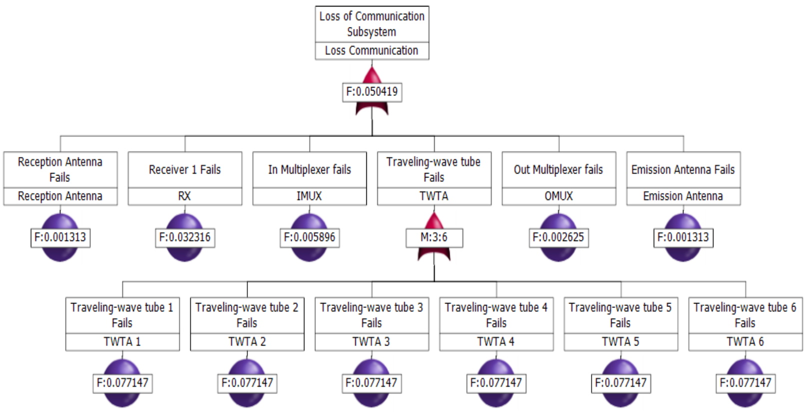


$$R_{Hypothetical\ Satellite} = 0.93 * R_{Avionics} * R_{Prop} * 0.9807 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.8400$$

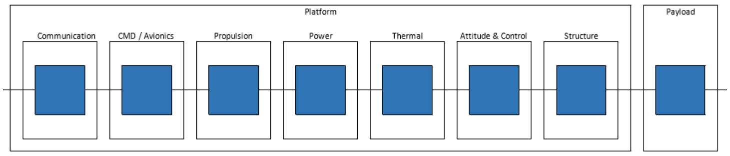
$$R_{Hypothetical\ Satellite} = 0.7661 * \left(R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc}\right)$$

And with the fully adjusted Communications subsystem

Unit	nb	Active Failure Rate fit	Passive Failure Rate fit	Use ratio (%)	Redundancy			Reliability at years **15**
Reception Antenna	1	**10**	1.0	100%	Active	1	/ 1	0.999
RX	1	250	25	100%	Active	1	1	0.968
IMUX (4-channel)	1	45	4.5	100%	Active	1	1	0.994
TWTA	1	611	61	100%	Active	4	6	0.992
OMUX	1	20	2	100%	Active	1	1	0.997
Emission Antenna	1	10	1	100%	Active	1	1	0.999
Communication Sub-System Reliability								**0.95**



Time	Unreliability
0	0.000000
13140.00	0.004402
26280.00	0.008842
39420.00	0.013371
52560.00	0.018031
65700.00	0.022859
78840.00	0.027885
91980.00	0.033136
105120.00	0.038632
118260.00	0.044389
131400.00	0.050419

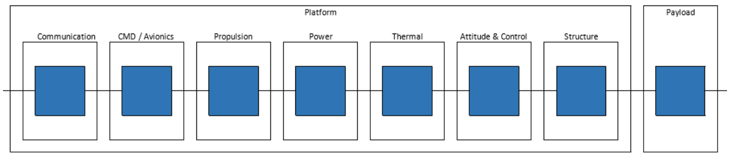


$$R_{Hypothetical\ Satellite} = 0.9493 * R_{Avionics} * R_{Prop} * 0.9807 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.8400$$

$$R_{Hypothetical\ Satellite} = 0.9039 * (R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc})$$

$$For\ 15\ more\ years\ of\ operation$$

Additionally, if all adjustments, cumulative Power (3.5), Communications (shown above), and Payload (shown in section 3.4) are applied to the system RBD, FT and PRA the following results are attained:



$$R_{Hypothetical\ Satellite} = 0.9493 * R_{Avionics} * R_{Prop} * 0.9712 * R_{Thermal} * R_{ACS} * R_{Struc} * 0.9494$$

$$R_{Hypothetical\ Satellite} = 0.8753 * (R_{Avionics} * R_{Prop} * R_{Thermal} * R_{ACS} * R_{Struc})$$

$$For\ 15\ more\ years\ of\ operation$$

While a system level FT (if completed) or payload-scenario PRA would be impacted by all these changes, the PMD PRA would be impacted by only the communications subsystem changes since PMD doesn't require the payload as shown below:

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr) = 0.9220 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr + 1500h)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(15yr)}$$

$$= \frac{R_{Comm'\ \&\ Power'} * R_{Avionics'} * R_{Prop'} * R_{ACS'-STT'\&\ GPSR'} * R_{STT'\&\ GPSR'} * R_{Struc'}}{0.9220 * R_{Avionics} * R_{Prop} * R_{ACS-STT\&\ GPSR} * R_{STT\&\ GPSR} * R_{Struc}}$$

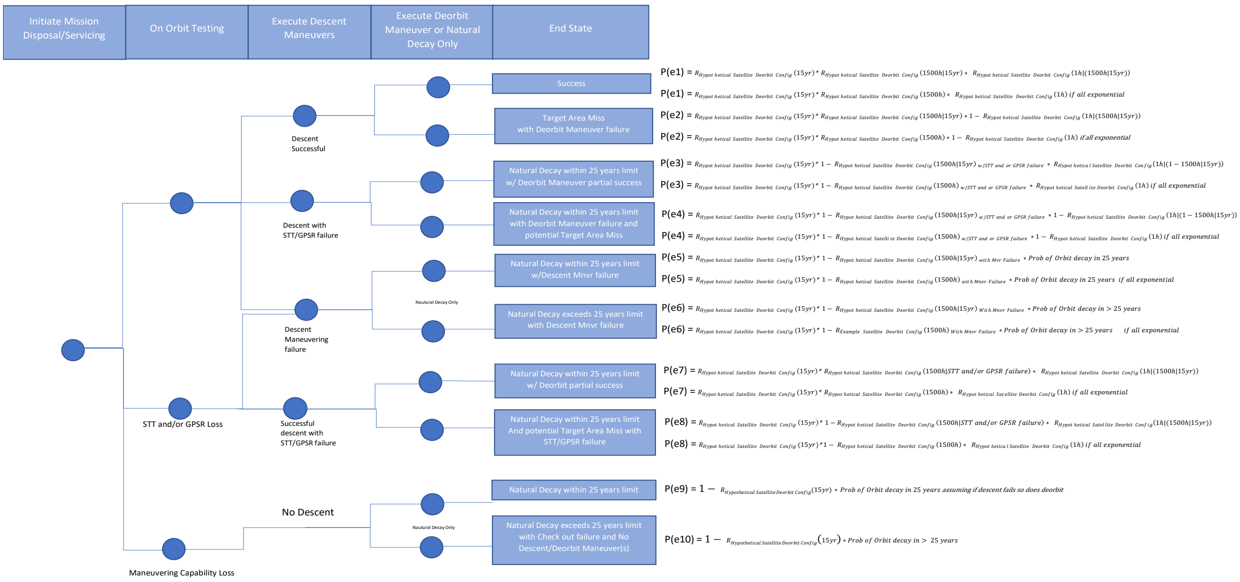
the prime variables indicate values after an additional 1500 hours of use with the new failure rate

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1h|(1500h|15yr)) = \frac{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1hr+1500h|15yr)}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$= \frac{R_{Comm''\ \&\ Power''} * R_{Avionic''} * R_{Prop''} * R_{ACS''-STT''\&\ GPSR''} * R_{STT''\&\ GPSR''} * R_{Struc''}}{R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)}$$

$$R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure\ w/STT\ and\ or\ GPSR\ failure} = R_{Hypothetical\ Satellite\ Deorbit\ Config}(1500h|15yr)_{With\ Mnvr\ Failure}$$

shown with shared event below since maneuvering (Comm/Power/Prop) is not dependent on STT and/or GPSR



4. Summary

Quantitative assessments, as shown above, should not be considered absolute predictions of future performance. But rather they should be performed to develop a figure of merit to compare options for a mission's continued viability and/or to show consistency with requirements (such as the deorbit 0.9 probability). Since any prediction's accuracy is limited by:

- Failure rate models being based on available data and the conditions under which the data was obtained/found, not being representative of the actual item or its use;
- Failure rate extrapolations that exceed the time or other stress-parameters of underlying use case used to determine the rate/distribution;
- Failure rates/distributions assuming unspoiled systems, so latent defects may cause unpredicted failures outside any prediction;
- Failure rates/distributions assume nominal usage not over-stressing which may cause unpredicted failures outside any prediction; and
- Underlying failure rates or distributions may not consider every possible event or be fully inclusive actual use case,

but can be improved with inclusion of performance data from a similar mission or use case.

Further, analyst performing any of the illustrations or examples shown on an actual mission will need revise the failure rate values, RBDs, FTs, and PRAs to reflect that mission's design and deorbit or operational scenarios to be assessed. Further, underlying assumptions should be validated for that mission and uncertainties/confidence-levels included with results to inform the intended decision-making stakeholders truly and fully.