New Method for Updating Mean Time Between Failure for ISS Orbital Replaceable Units

Consultation Report

December 1, 2005

NESC Request No. 05-163-E

VOLUME I: REPORT

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1.0 Authorization and Notification

This request to conduct a peer review of the International Space Station (ISS) proposal to use Bayesian methodology for updating Mean Time Between Failure (MTBF) for ISS Orbital Replaceable Units (ORU) was submitted to the NASA Engineering and Safety Center (NESC) on September 20, 2005.

The request was presented and the plan approved by the NESC Review Board (NRB) on October 6, 2005. This final report with recommendations to the ISS Program was presented to the NRB on November 17, 2005.

2.0 Signature Page

Consultation Team Members

_______________________________ Vickie S. Parsons, NESC

_______________________________ Vitali Volovoi

_______________________________ James Womack

3.0 List of Team Members

Name	Title	Affiliation
Vickie Parsons	NESC Systems Engineer	LaRC
Vitali Volovoi	Statistical Consultant	Georgia Institute of Technology, School of Aerospace Engineering
James Womack	Statistical Consultant	Aerospace Corporation
	Support	
Cindy Bruno-Miller	Program Analyst, MTSO	LaRC
Elizabeth Holthofer	Technical Writer	ViGYAN, Inc., LaRC

4.0 Executive Summary

The ISS Program requested a peer review of their proposal to use operational data to update the MTBF for ISS ORUs by applying Bayesian methodology. The results were requested by October 20, 2005 in order to be available during the process of reworking the current ISS flight manifest.

After a review of the documentation provided by the ISS Program and discussion with the principle contributors to the proposal, the statistical peer review team concluded that applying Bayesian methodology is an appropriate approach for updating MTBF estimates. However, several assumptions used in this particular application should be refined in order to preclude overly optimistic estimates. Specifically, the selection of α, the justification for excluding degradation, and the categorization of ORUs need to be re-visited.

5.0 Consultation Plan

This consultation consisted of a peer review by statistical experts of the proposed application of Bayesian methodology to revising MTBF estimates for ISS orbital replacement units. Each member of the review team analyzed the following documents and files:

- Fisher – Price Report (Space Station Freedom External Maintenance Task Team Final Report), July 1990.
- Bayesian Methodology and How It Could Apply to ISS-USOS External ORU MTBFs, Jean Ni, August 29, 2005.
- Estimation of Prior Distribution Parameter α Used in Bayesian Methodology -2, Jean Ni, September 13, 2005.
- Estimation of Prior Distribution Parameters Used in Bayesian Methodology, Jean Ni, June 23, 2005.
- Hubble Space Telescope Reliability Assessment, July 2002 Model, Helen Wong, November 21, 2002.
- Various Excel spreadsheets for Bayesian calculations by ISS.
- Modeling Analysis Data Set (MADS) for ISS ORU manufacturers' estimated failure rates

A telephone conference was conducted between the peer review members and representatives of the ISS Program responsible for the proposal, where questions and details were pursued. Two additional telephone conferences and email exchanges resulted in the final peer review results and recommendations that follow.

6.0 Description of the Problem, Proposed Solutions, and Risk Assessment

The ISS Program proposed the application of Bayesian methodology to revise (increase) the MTBF estimates for ORUs. The risk inherent in increasing the MTBF estimates would be a failure to have necessary replacements if the MTBFs are overly optimistic. During the analyses of the proposal, the statistical peer review team identified several areas of concern, explained in the following sections.

7.0 Data Analysis

Selection of the prior distribution parameter α is the most important and difficult aspect of applying the Bayesian methodology to updating reliability estimates. The values of α under consideration for use in ISS ORUs are between 0.1963 and 1.5582, which are smaller then typical values used in other space programs.[1] These values were derived from various random failure rate estimates (the shape parameter) provided in the Fisher-Price report[2] and manufacturer data on individual components (the scale parameter) contained in the MADS dataset.[3] Small values for α correspond to wide confidence bounds for prior estimated failure rates and lead to discounting the prior information. Values smaller than 1.368 are outside of a meaningful range as described in the detail calculation section.

Determining the best value of α would require determining the uncertainty in the original failure rate of each individual ORU. All of the assumptions and uncertainties used to estimate each part failure rate in the ORU would needed to be modeled by a statistical distribution from which it would be possible to determine the distribution of the ORU failure rate. This however is a very difficult and time-consuming process.

A simpler approach for selecting an α value was used by the Hubble and Tracking and Data Relay Satellite (TDRS) Programs. They used an α value of 2.2068, which was determined by setting the probability that λ is less than $\lambda_0/5$ equal to 5 percent.[4] This models the assumption that there is only a small probability that the original failure rates are larger then five times the true failure rate. Use of 5 percent is a typical rule of thumb for statistical significance. The recommended 1.56 by the ISS Program yields a corresponding probability of 10 percent. The 2.2068 value of α has undergone extensive review by the Hubble Program. The prior distribution for α = 2.2068 (see Figure 1 in Appendix B) has a much more reasonable shape for modeling the uncertainty in the original failure rate. Also, it has proven to provide good reliability updates for the TDRS Program, in line with updates calculated by other acceptable reliability estimating methods.[5]

Exponential distributions dominated the reliability world for decades due to the simplicity of the systems analysis with exponentially distributed failures and the need for only one parameter,

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[1] Ni, Jean. "Estimation of Prior Distribution Parameter "alpha" Used in Bayesian Methodology-2." PowerPoint Presentation, Johnson Space Center, 13 September 2005.
[2] Space Station Freedom External Maintenance Task Team, Final Report. NASA, July 1990.
[3] Modeling Analysis Data Set (MADS).
[4] Wong, Helen. "Hubble Space Telescope Reliability Assessment, July 2002 Model." The Aerospace Corporation, Report No. TOR – 2003 (2154) – 2352, 21 November 2002.
[5] Womack, James. "Tracking and Data Relay Satellite Reliability Models." The Aerospace Corporation, Report No. TOR-2005 (2141) – 3876, 26 January 2005.

failure rate or its inverse, mean time between failures (MTBF), as opposed to at least two required to define other distributions. The latter consideration was (and still is) of great importance when there is a shortage of the data needed to characterize the failure pattern statistically. The use of an exponential distribution to describe "random" failures can be complemented by deterministic life limits for units that are known to degrade with time. However, for some failure modes (especially for mechanical components), the degradation is gradual, and so is the corresponding increase in failure rate. This continuous increase in the failure rate is not limited to the end of life, and is usually described, depending on the type of degradation, either by a Weibull distribution with the shape parameter $\beta > 1$ or by a LogNormal distribution. The ISS proposal assumes an exponential distribution of the failure frequencies, thus ignoring the degradation of individual units. The MADS dataset indicates that manufacturers' estimates of Weibull shape parameter β range from 2.5 to 5.0, which raises the concern than degradation should not be ignored. The calculations for inclusion of failures obeying Weibull distributions into the Bayesian updating procedure can be found in Womack's report.[6]

Several assumptions within the Fisher-Price report were accepted by the ISS Program without explanation.[7] One concern for this peer review team was the logic associated with grouping large sets of diverse components into four categories. The Fisher-Price method for aggregation of failure estimates for the analog study was not explained in the portion of the Fisher-Price provided to this peer review team.[8] Then, the final Bayesian methodology is planned to be applied to all ORUs uniformly.

This ISS proposal, as currently presented or with the recommendations cited in this report, can lead to counterproductive results by removing conservatism from the estimation of the failure rates, unless this is supplemented with the rigorous risk analysis for over and under predicting the amount of spares required. This is due to the fact that under-predicting the amount of spares has greater consequences that over-predicting, and an initial conservatism in estimating MTBF compensated for this inequality.

[6] Ibid.
[7] Space Station Freedom External Maintenance Task Team, Final Report. NASA, July 1990.
[8] Ibid.

8.0 Findings, Observations, and Recommendations

F-1 Small values for α correspond to wide confidence bounds for prior estimated failure rates and lead to discounting random failure rate estimates (the shape parameter - Fisher-Price report[9]) and manufacturer data on individual components (the scale parameter) contained in the MADS dataset. Values smaller than 1.368 for α are outside of a meaningful range.

F-2 The MADS indicates that manufacturers' estimate of β range from 2.5 t 5.0, which raises the concern that degradation should not be ignored.

F-3 The use of an exponential distribution complemented with establishing deterministic life limits for units known to degrade with time can lead to overly optimistic prediction, since units can degrade gradually, resulting in continuously increasing failure rate.

F-4 The risk inherent in increasing the MTBF estimates would be a failure to have necessary replacement if the MTBFs are less conservative.

R-1. Within the Bayesian methodology for MTBF estimates, use a value of α = 2.2068 until additional analysis can show cause for another value. (F-1)

R-2. Validate the β values within the MADS. (F-2)

R-3. If β values within the MADS are indeed greater than 2.0, adjust the Bayesian methodology to include consideration of those degradation values, even though the unit life cycle is considerably greater than the expected life cycle of the ISS. (F-2)

R-4. Investigate some of the more critical components individually for MTBF. (F-3)

***R-5.* Rather than rely solely on MTBF estimates, maintain cognizance of the associated risk analyses and schedule replacements accordingly**. (F-4)

[9] Ibid.

9.0 Lessons Learned

None.

10.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment/inspection team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan.
Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 List of Acronyms

HST	Hubble Space Telescope
ISS	International Space Station
MADS	Modeling Analysis Data Set
MTBF	Mean Time Between Failure
NASA	National Aeronautic and Space Administration
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
ORU	Orbital Replaceable Units
TDRS	Tracking and Data Relay Satellite

12.0 References

Modeling Analysis Data Set (MADS).

Ni, Jean. Bayesian – Final PowerPoint Presentation – August 29, 2005, ISS Program Office.

______. "Estimation of Prior Distribution Parameter "alpha" Used in Bayesian Methodology-2." PowerPoint Presentation, Johnson Space Center, 13 September 2005.

Space Station Freedom External Maintenance Task Team, Final Report. NASA, July 1990.

Womack, James. "Tracking and Data Relay Satellite Reliability Models." The Aerospace Corporation, Report No. TOR-2005 (2141) – 3876, 26 January 2005.

Wong, Helen. "Hubble Space Telescope Reliability Assessment, July 2002 Model." The Aerospace Corporation, Report No. TOR – 2003 (2154) – 2352, 21 November 2002.

13.0 Minority Report

There are no dissenting opinions in this report.

VOLUME II: APPENDICES

Appendix A. NESC Request Form (PR-003-FM-01)

NASA Engineering and Safety Center Request Form

Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 9/20/2005 12:00 AM	Status: New	Reference #: 05-163-E
Initiator Name: Neil Lemmons	E-mail: neil.lemmons-1@nasa.gov	Center: JSC
Phone: (281)-244-8080, Ext _____	Mail Stop: OM	
Short Title: New Method for Updating Mean Time Between Failure		
Description: Jay Leggett got a call from Neil Lemmons(JSC) in the ISS program and he is requesting a peer review of an assessment that he performed (or someone in his group) on using ISS Orbital Replaceable Unit (ORU) operational data to update Mean Time Between Failure (MTBF) by applying Bayesian methodology. Updating the MTBF for ORUs is important in setting payload requirements for future missions (ATV, HTV, SSP). The current flight manifest is being reworked and this analysis could play a role in manifest needs. Neil mentioned that the a manifest decision is targeted for the end of October. Neil Lemmons would be the initiator. Is there anything else that you need on this? This looks like something that would fall in Vickie's court. Thanks, Jay		
Source (e.g. email, phone call, posted on web): phone		
Type of Request: assessment		
Proposed Need Date: 10/20/2005		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 9/20/2005 12:00 AM		
Potential ITA/I candidate? ☒Yes ☐ No		
Assigned Initial Evaluator (IE): Vickie Parsons		
Date assigned (mm/dd/yyyy): 9/26/2005		
Due date for ITA/I Screening (mm/dd/yyyy): 10/6/2005		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? ☐Yes ☐ No		
If yes:		
Description of action:		
Actionee:		
Is follow-up required? ☐Yes ☐ No If yes: Due Date:		
Follow-up status/date:		
If no:		
NESC Director Concurrence (signature):		
Request closure date:		

NESC Request Form
NESC-PR-003-FM-01, v1.0
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Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? ☐Yes ☐ No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		
Section 4: NRB Review and Disposition of NCE Response Report		
ITA/I Approved: ☐Yes ☐ No	Date Approved:	Priority: - Select -
ITA/I Lead: , Phone ( ) - , x		
Section 5: ITA/I Lead Planning, Conduct, and Reporting		
Plan Development Start Date:		
ITA/I Plan # NESC-PL-		
Plan Approval Date:		
ITA/I Start Date	Planned:	Actual:
ITA/I Completed Date:		
ITA/I Final Report #: NESC-PN-		
ITA/I Briefing Package #: NESC-PN-		
Follow-up Required? ☐Yes ☐ No		
Section 6: Follow-up		
Date Findings Briefed to Customer:		
Follow-up Accepted: ☐Yes ☐ No		
Follow-up Completed Date:		
Follow-up Report #: NESC-RP-		
Section 7: Disposition and Notification		
Notification type: - Select -	Details:	
Date of Notification:		
Final Disposition: - Select -		
Rationale for Disposition:		
Close Out Review Date:		

NESC Request Form
NESC-PR-003-FM-01, v1.0

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Form Approval and Document Revision History

Approved: ____________________________ NESC Director ________ Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

Appendix B. Details of Calculations and Considerations by Peer Review Team

The Bayesian methodology is used to incorporate on-orbit experience into preexisting ORU reliability models. It is assumed here that the failure distribution of an ORU has an exponential distribution, that is, the ORU has a constant failure rate[10]. The ORU failure is denoted by λ, and can be equivalently represented by its inverse, a mean time between failures (MTBF). The failure rate is usually estimated using piece part reliability models where the failure rates of the individual parts are obtained from reliability handbooks (e.g. MIL-HDBK-217) and incorporate part quality, operating environment and temperature, and duty cycle. The Bayesian methodology models λ as a random variable with a gamma distribution called the prior distribution. The gamma density function is

$$f(\lambda) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\beta\lambda}$$
$$\lambda, \alpha, \beta > 0$$

The mean of the gamma distribution is α/β and is set equal to the initial ORU failure rate, say λ_0. By setting $\beta = \alpha/\lambda_0$ the prior distribution is characterized by the single parameter α. The on-orbit lifetime data of the ORU is incorporated into the model by computing the conditional distribution of λ given the observed lifetime data. This is called the posterior distribution and turns out to be a gamma distribution with parameters:

$$\alpha_{post} = \alpha + s \text{ and } \beta_{post} = \beta + t \text{ .}$$

Where s = observed ORU failures, t = total operating time of the ORU. The updated failure rate is usually estimated by the mean of the posterior distribution given by

$$\frac{\alpha_{post}}{\beta_{post}} = \frac{\alpha + s}{\beta + t}$$

The prior density is intended to model our uncertainty in our original failure rate λ_0 of the component. Figure 1 is a plot of the prior density function for several values of α each with a mean equal to λ_0.

[10] Other Bayesian methods are available for non-constant failure rate distributions.

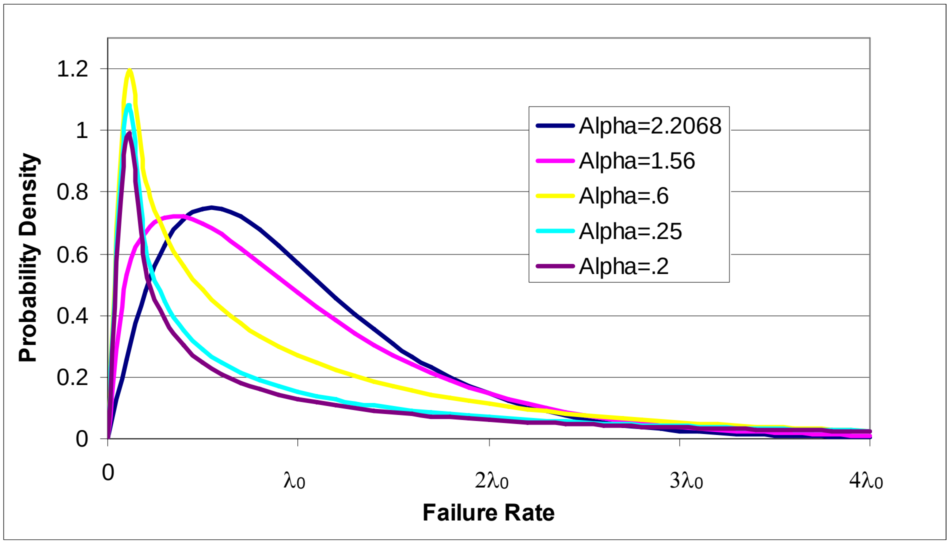

Figure 1. Prior Density Functions

From Figure 1 we see the affect of α on the prior density. The smaller α is the more we bias the model toward smaller failure rates. The α values for the ISS Program were selected by fitting the prior distribution to failure rates given in the Fisher-Price report.[11] Table 6.1. Table 6.1 in Jean Ni;s Bayesian presentation contains a mean, 5-percentile, median, and 95-percentile of failures rates for groups of ORUs under a number of assumptions.[12] Because these failure rate distributions contain the variability of failure rates for groups of different ORUs the resulting distribution has a large variance as compared to the variance of a single ORU. Fitting an α to these distributions with large variances will result in values of α that are too small.

Considering the BCDU that experienced no failures during a total time of 236448 hours.[13] Using α=0.6065 for electronics components, there is a 95 percent confidence that MTBF will be at least 137076 hours.[14] In contrast, using classical statistics based on the operational data only, the 95 percent confidence interval based on χ^2 statistics yields 78928.3. The Bayesian procedure is designed to adjust an initial estimate based on the operational data and implies that the updated result will be somewhere between prior and operational prediction, which is clearly violated here. For comparison, the lower limit of α=1.368 for a "reasonable value"

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[11] Space Station Freedom External Maintenance Task Team, Final Report. NASA, July 1990.
[12] Ni, Jean. Bayesian – Final PowerPoint Presentation – August 29, 2005, ISS Program Office.
[13] Womack, James. "Tracking and Data Relay Satellite Reliability Models." The Aerospace Corporation, Report No. TOR-2005 (2141) – 3876, 26 January 2005. (Slide 11)
[14] "Bayesian Methodology and How It Could Apply to ISS-USSOS External ORU MTBFs." Saber, August 2005. (Slide 8)

recommended by HST program provides 95 percent confidence lower bound for MTBF as 60775 hours, while the value $\alpha=2.2068$ selected by HST yields in this situation 37674.7 hours.

The main concern with the grouping of distinct units into broad categories is that the bounds in the Fisher-Price report reflect variability among different ORUs and not an uncertainty about the failure rate for a given ORU.[15]

category	λ (50th)	λ (95th)	λ (95th)/λ (50th)
electrical	3.33333E-07	7.41174E-06	22.23523395
electronic	4.46828E-06	3.92866E-05	8.792331264
eletromech	4.87876E-06	1.96078E-05	4.019019608
mechanical	4.02253E-07	7.36377E-06	18.30633284

Table 1. MTBF Variability Due to Grouping ORU into Four Categories Based on MADS

The distinction between the two is important since the former is an artifact of the grouping into a category, rather than a property of an individual ORU. If the contribution to the resulting bounds from the variability between different ORUs within a category is significant, the result is an excessively wide confidence interval, a smaller value of α and unjustified discounting of the importance of the prior. This effect can potentially explain unusually small values of α that were obtained from the "synthesis data."

[15] Space Station Freedom External Maintenance Task Team, Final Report. NASA, July 1990.

	λ(5th)	λ(50th)	λ(95th)	λ(95th)/λ(50th)	α
syntheses					
electrical	1.45E-08	4.08E-07	1.15E-05	2.82E+01	0.2481
electronic	2.06E-07	1.39E-06	9.40E-06	6.76E+00	0.6065
electro_mech	2.31E-08	1.19E-06	6.17E-05	5.18E+01	0.1972
mechanical	2.22E-08	1.16E-06	6.09E-05	5.25E+01	0.1963
work package					
electrical	5.10E-07	1.84E-06	6.62E-06	3.60E+00	1.3024
electronic	4.70E-07	3.19E-06	2.16E-05	6.77E+00	0.6056
electro_mech	7.93E-08	2.01E-06	5.07E-05	2.52E+01	0.2606
mechanical	2.75E-07	1.77E-06	1.14E-05	6.44E+00	0.6352
combination					
combination-analog study	1.67E-06	5.35E-06	1.73E-05	3.23E+00	1.5582
combination-synthesis	2.09E-07	8.42E-07	3.41E-05	4.05E+01	0.2150
combination-work package	2.45E-07	2.01E-06	1.65E-05	8.21E+00	0.5115

Table 2. Deriving α Based on Fisher & Price Report Data Taken from Slide 5 *Estimation of Prior Distribution Parameter α Used in Bayesian Methodology-2 September 13th 2005, AI# 103 update*[16]

The Table 1 shows variability within a category based purely on the MTBF provided in MADS. This should be compared with the Table 2 that is reproduced the results presented by ISS. It can be observed that for the electrical and electronic components the numbers from Table 1 are reasonably close to the numbers from the "syntheses" set of data in the Table 2, showing that at least for these two categories the ratio between the 95 percent and median values for failure rate can be attributed to the grouping effects.

[16] Ibid.

Document Revision History

Approved:	Original signed on file	12/8/05
	NESC Director	Date

Version	Description of Revision	Author	Effective Date
1.0	Initial Release	Principal Engineer's Office	