

Technical Report ARAET-TR-05018

IMPROVING RELIABILITY BY REDUCING TOLERANCE STACK-UP FAILURES

S. Recchia
J. A. Cordes
ARDEC

Marc Worthington, MS
Aerospace Engineer
KDI Precision Products, Inc.
3975 McMann Road Cincinnati, OH 45245

Mohammad R. Khalessi, PhD
PredictionProbe, Inc.
2192 Dupont Drive, Suite 205
Irvine, CA 92612

December 2005



ARMAMENT RESEARCH, DEVELOPMENT AND
ENGINEERING CENTER

Armaments Engineering & Technology Center

Picatinny Arsenal, New Jersey

Approved for public release; distribution is unlimited.

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

The citation in this report of the names of commercial firms or commercially available products or services does not constitute official endorsement by or approval of the U.S. Government.

Destroy this report when no longer needed by any method that will prevent disclosure of its contents or reconstruction of the document. Do not return to the originator.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-01-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden to Department of Defense, Washington Headquarters Services Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) December 2005		2. REPORT TYPE Interim		3. DATES COVERED (From - To) Jan 2005 to Jun 2005	
4. TITLE AND SUBTITLE IMPROVING RELIABILITY BY REDUCING TOLERANCE STACK-UP FAILURES				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHORS S. Recchia and J. A. Cordes, ARDEC M. R. Kahlessi, PredictionProbe, Inc. M. Worthington, KDI Precision Products, Inc.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Commander U.S. Army ARDEC Fuze and Precision Armaments Technology (AMSRD-AAR-AEP-E) Picatinny Arsenal, NJ 07806-5000 (continued)				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) ARDEC, EM Technical Research Center (AMSRD-AAR-EMK) Picatinny Arsenal, NJ 07806-5000				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) Technical Report ARAET-TR-05018	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for pubic release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <p>Excalibur is the Army's 155-mm guided bullet for howitzers. Once fielded, Excalibur is expected to have a reliability of 90%. This paper describes a method to predict the reliability of the locking mechanism in the fuze safe and arm device. Hand calculations showed that a locking failure could occur if several dimensions were machined close to a tolerance limit in the same device. The probability of a locking failure was estimated using Monte Carlo simulations and a First Order Probability method. The governing equation was a function of about a dozen other equations and 21 variables. A probability distribution function described each variable's nominal dimension and tolerance. Both Monte Carlo simulations and First Order Probability methods predicted fewer than 35 failures in a million devices. Output also included a ranking of dimensions and tolerances and their relative effect on reliability.</p>					
15. SUBJECT TERMS Excalibur, Reliability, Probability, Monte Carlo, Dimensions, Tolerance, Locking, Over closure, Stack-up, and Inspection					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 18	19a. NAME OF RESPONSIBLE PERSON J.A. Cordes, etc.
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (973) 724-6147

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSES (continued)

Aerospace Engineer
KDI Precision Products, Inc.
3975 McMann Road
Cincinnati, OH 45245

PredictionProbe, PhD
2192 Depont Drive, Suite 205
Irvine, CA 92612

CONTENTS

	Page
Introduction	1
Method	2
Probability Analysis	2
Geometry of Governing Equations for Locking Mechanism	3
Results	5
Probability of Failure	5
Sensitivity Analysis	5
Discussion	7
Sources of Error	7
Using this Case Study for Inspection Criteria	8
Conclusions and Recommendations	9
References	11
Distribution List	13

FIGURES

1	Fuze safe and arm device	1
2	Probability distribution of dimensions	3
3	Dimensions and equations used for analysis	3
4	Sensitivity of reliability to average dimensions	6
5	Sensitivity of reliability to standard deviations	7
6	First order reliability method, error region	8

INTRODUCTION

The Army's Excalibur is a 155-mm guided projectile. Excalibur has four key performance parameters: accuracy, effectiveness, reliability, and interoperability. Reliability is the probability that the projectile meets its mission without any failure. One of the precursor projectiles to Excalibur, the 155-mm M898 Sense and Destroy Armor (SADARM), did not meet its key performance parameter for reliability in part due to tolerance stack-up failures in one of its sensors. In several early tests, over-closure caused binding of the sensor and SADARM failed to operate as designed.

A large part of a projectile's mission is to guarantee the safety of the soldiers using the round. For this analysis, reliability deals with the probability that the round is safe when unarmed. Another part of the projectile's mission is that the round arms at the right time. In some cases, the parameters that change the safety of the round also inversely affect the ability for the round to arm itself. A careful balance must be acquired between these two objectives.

To meet Excalibur's reliability parameter of 90%, tolerance stack-up analysis is routinely done on all sensors, mechanisms, and sub-systems. One of the sub-systems effecting reliability is the fuze safe and arm device (FS&A). The FS&A is the mechanism that governs the timely arming of Excalibur.

Figure 1 shows a small part of the FS&A device (more details cannot be shown). For safe operation, the rotor D-lock link must be in the correct position when Excalibur is unarmed. About 20 dimensions affect the accurate positioning of the rotor D-lock within the rotor slot. Each dimension has a tolerance range. Preliminary analysis showed that if several parts were machined to the extreme dimensions of their tolerances, the rotor D-lock would not clear the locking slot and the mechanism would remain (incorrectly) in the unlocked position. This failure would not only lower the reliability of Excalibur, it could render the projectile unsafe.

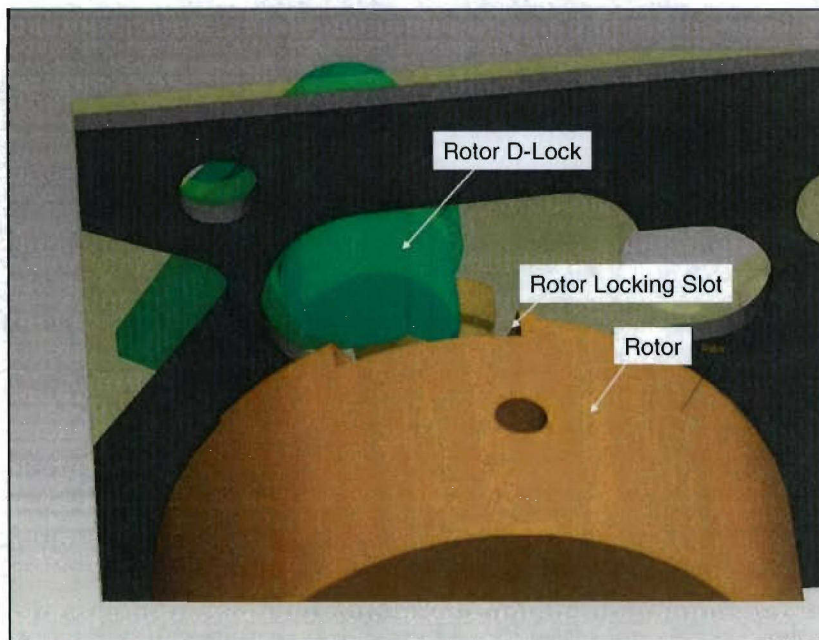


Figure 1
Fuze safe and arm device (small section)

Probabilistic analysis was performed to determine the likelihood that the FS&A would not lock as designed. UNIPASS software (ref. 1) was used to perform the probabilistic analysis. Two probabilistic methods were used to perform the analysis including the Monte Carlo Method and First Order Reliability Method. The Monte Carlo method predicted improper locking would occur less than one time in a million mechanisms. The First Order Reliability method estimated 32 failures in a million mechanisms. The sensitivity measures provided by the First Order Reliability method were used to identify which dimensions and tolerances could be changed to improve reliability.

METHOD

Probability Analysis

The probability of success or failure was defined by mathematical relations between two dimensions in the FS&A device:

$$0 < S1(y) - s2(y) \text{ safe} \quad (1)$$

$$0 \geq S1(y) - s2(y) \text{ fail} \quad (2)$$

where

$S1(y)$ = distance from the datum to top of locking slot

$S2(y)$ = distance from the datum to the bottom most corner of the D-lock

When equation 1 is satisfied, the FS&A operates as designed and the rotor D-lock is locked into the rotor slot.

Two probability simulations were completed to estimate the reliability of the FS&A. First, the Monte Carlo simulation used a high number of iterations. At every iteration, a random value was chosen between the upper and lower limits of each dimension function. A second simulation, a First Order Reliability method (refs. 2 through 4), was used to validate the Monte Carlo simulation. The First Order Reliability simulation used multiple iterations to define a most probable point of failure (MPP). It then varied each dimension from the MPP to determine the probability of failure.

All dimensions were inserted into the analysis as a probability distribution shown in figure 2. Each dimension has a lower limit XL and an upper limit XU. The upper and lower limits were determined from the nominal dimension and its tolerances. For example:

$$\text{If Dimension} = \text{nominal} \pm \text{tolerance} = 100 \pm 0.05$$

$$\text{Then XL} = 99.95 \text{ and XU} = 100.5$$

Results were calculated for the 'Hard Boundary' in figure 2. The 'Soft Boundary' might be used for less than 100 % inspection of a dimension or where errors in the inspection occurred. Other possibility distributions could also be used for dimensions.

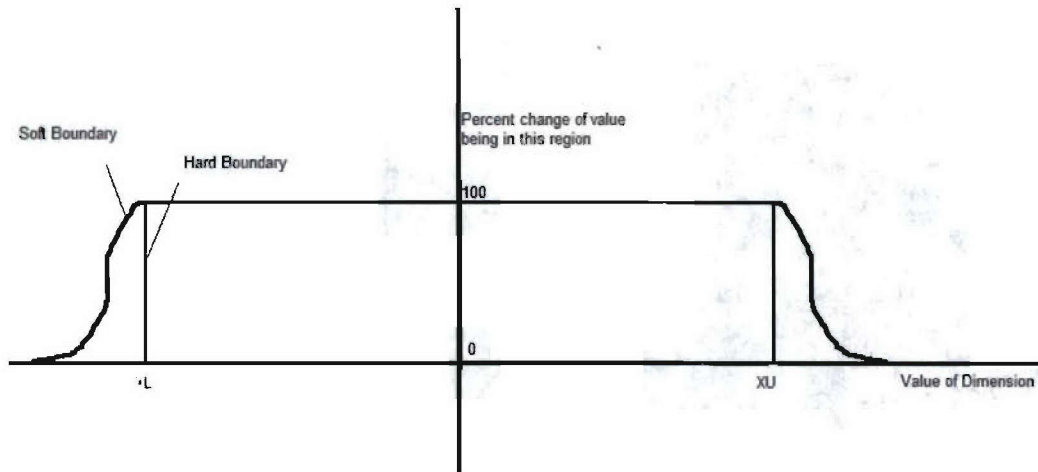


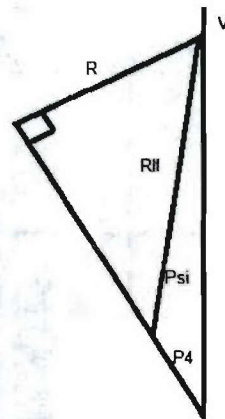
Figure 2
Probability distribution of dimensions

Geometry and Governing Equations for Locking Mechanism

The equations for the dimensions affecting the rotor locking mechanism were generated. Figure 3 shows equations that were used for the probability analysis. Each dimension is referenced from the datum line in figure 3c.

$$\begin{aligned}
 0 &= s2(y) - S1(y) \\
 s2(y) &= By + (Bh - Rdl) \cdot \sin(\text{bang}) + Rdl \cdot \sin(\beta) \\
 S1(y) &= Ay + (Ah - axle) \sin(\text{angle}) - Rrotor \cdot \sin(\alpha) \\
 H2 &= Qx + (Bh - Rdl) \cdot \cos(\text{bang}) + (BSh2 - Sls) \cdot \cos(\text{pang}) \\
 L &= Qy + (Bh - Rdl) \cdot \sin(\text{bang}) + (BSh2 - Sls) \cdot \sin(\text{pang}) \\
 I &= \sqrt{H2^2 + L^2} \\
 \psi &= \arctan\left(\frac{H2}{L}\right) - \arccos\left(\frac{RI^2 - Rss^2 - I^2}{-2 Rss \cdot I}\right)
 \end{aligned}$$

(a)



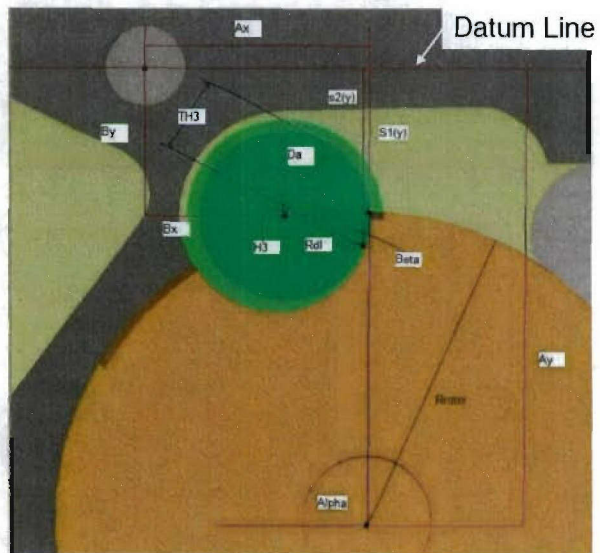
$$P4 = \pi - \arccos\left(\frac{R5}{Rdl}\right) + \psi$$

$$Da = P4 + 2\left(\frac{\pi}{180}\right)$$

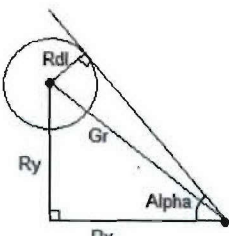
(b)

$$H3 = Rdl - TH3$$

$$\beta = \frac{-\pi}{2} + Da + \arccos\left(\frac{H3}{Rdl}\right)$$



(c)

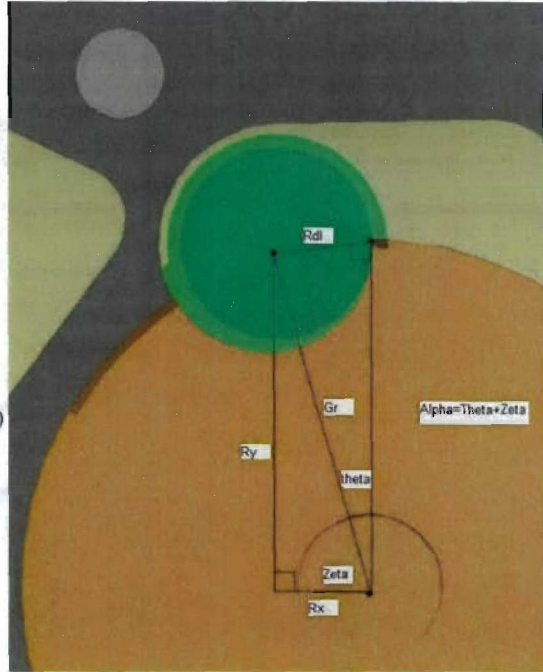


$$Ry = Ay + (Ah - axle) \cdot \sin(\text{angle}) - By + (Bh - Rdl) \cdot \sin(\text{bang})$$

$$Rx = Ax + (Ah - axle) \cdot \cos(\text{angle}) - Bx + (Bh - Rdl) \cdot \cos(\text{bang})$$

$$Gr = \sqrt{Ry^2 + Rx^2}$$

$$\alpha = \text{atan}\left(\frac{Ry}{Rx}\right) + \text{asin}\left(\frac{Rdl}{Gr}\right)$$



(d)

Figure 3
Dimensions and equations used for analysis

The dimensions left out of figure 3 are locating angles: bang, angle, and pang. Locating angles define where the axle touches the mating hole. These angles ranged between zero and 2π radians.

RESULTS

Probability of Failure

The results of the Monte Carlo simulation indicated that the mechanism would fail to lock in less than one in a million devices. The First Order Reliability method used 137 iterations and returned a First Order Reliability of approximately 0.9999678.

Sensitivity Analysis

The First Order Reliability simulation was also used for a sensitivity analysis. The dimensions and tolerances that have the largest effect on the reliability calculations were determined. Sensitivity analyses were completed on the average and tolerance range for each dimension.

Figure 4 shows the relative sensitivity of the average dimensions. Some values are in the positive y region and some values are in the negative y region. If the value is positive, then an increase in the average dimension will increase reliability. Increasing the average dimension for

by, rrotor, radius5, qy, and th3 would increase the reliability of the FS&A; for example, a dimension such as 100 ± 0.05 . The importance of each dimension to the reliability is shown by its magnitude. For example, if the nominal dimension of rrotor is raised by 20%, the reliability will increase more than if the nominal dimension of qy is raised by 20%. If the value in figure 4 is negative, a decrease in the average value of ay and rll will increase the reliability. When changing the nominal values, the tolerances remain the same.

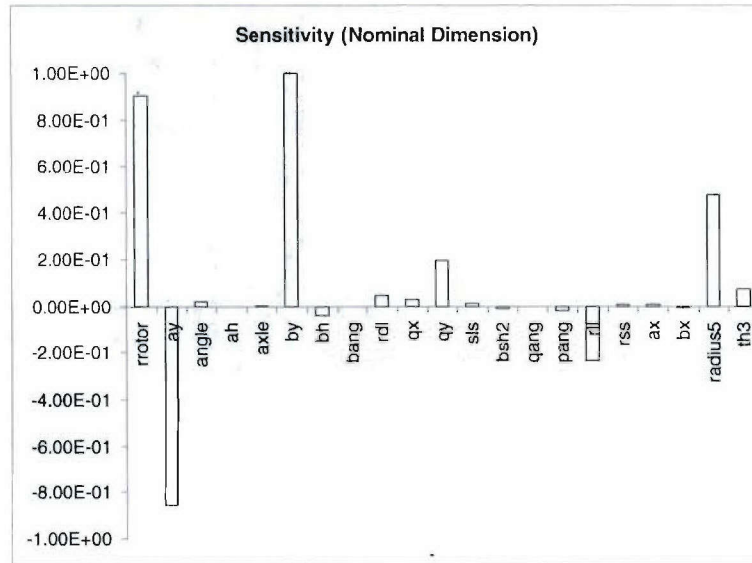


Figure 4
Sensitivity of reliability to average dimensions
(comparison of the Mean*dbeta/dmean for each constant)

The sensitivity analysis of the mean values was checked using Excel. Equation 1 was generated at mean values. Results were compared to results where constants were increased by 20%. In each case, the sensitivity in the Excel calculations agreed with the Unipass ranking.

Figure 5 compares standard deviations. If the value is below 0, then a tighter tolerance will improve reliability. If the value is above 0, then increasing the tolerance improves the reliability. From figure 5, decreasing the tolerances on dimensions radius5 and by would improve the reliability of the FS&A. The tolerances of pang, angle, and bang cannot be decreased because they are locating angles with a value of $\pi \pm \pi$ radians. Not surprising, increasing the tolerances will not improve the reliability of the FS&A. However, figure 5 shows which tolerances have minimal effect on reliability. This information could be used to generate inspection criteria or decrease the cost of manufacturing.

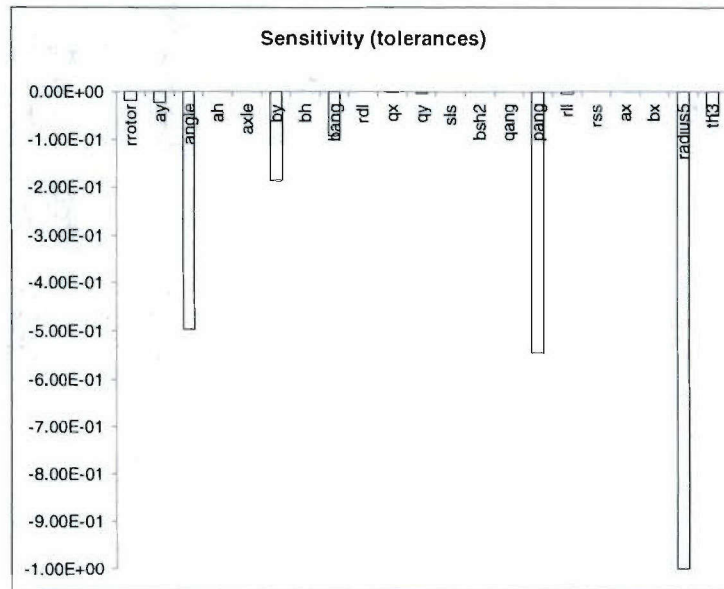


Figure 5
Sensitivity of reliability to standard deviations
(function: $\text{dbeta}/\text{d_standard deviation}$)

The sensitivity analysis also indicates dimensions that do not significantly affect the reliability of the FS&A. The following dimensions have minimal effect on the locking mechanism: **ah**, **axle**, **sls**, **bsh2**, **qang**, **rss**, **ax**, and **bx**.

DISCUSSION

Sources of Error

Errors in Accuracy

The methods provide an estimate of reliability and a ranking of the dimensions and tolerances that affect the reliable function of the FS&A. The actual distributions of the dimensions are unknown. Without the exact distributions, the reliability values should be considered as an order-of-magnitude answer rather than an absolute reliability value.

Errors in the Dimensional Variations

It was assumed that dimensions have a uniform distribution between the hard upper and hard lower boundaries (fig. 2). If the actual dimensions of multiple parts could be tracked, the accuracy of the distribution in figure 2 could be assessed and improved.

Errors Due to Inspection

It was assumed that all dimensions would be inspected 100% and that all inspections would be accurate. If the inspection is inaccurate or if only partial inspection is completed, then the hard boundaries shown in figure 2 are inaccurate. Soft boundaries could be used to incorporate probability density functions for XL and XU .

Errors in the First Order Method

Another source of error is in the First Order Reliability method. As shown in figure 6, this method assumes that there is a straight line that separates the regions of pass and failure. This may not be the case.

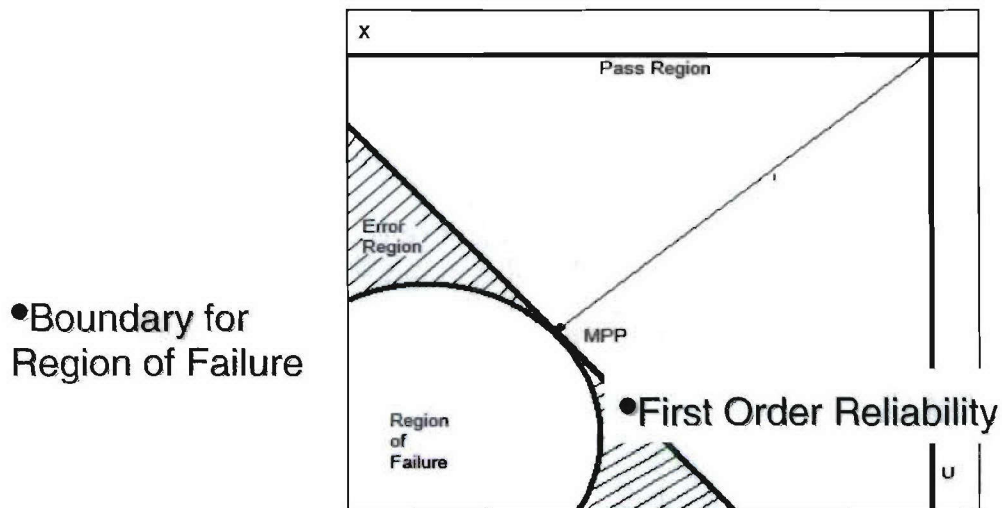


Figure 6
First order reliability method, error region

Using this Case Study for Inspection Criteria

The sensitivity analysis has implications for component inspection. From the sensitivity analysis, the following dimensions should be inspected to 100% or inspected as a safety critical characteristic:

- Based on sensitivity of the mean, 100% inspection: **ay**, **rrotor**, **by**, **qy**, **rlI**, **radius5**
- Based on sensitivity of the standard deviation, 100% inspection: **radius5**, **by**

In a similar fashion, some of the variables had little effect on the reliability of the FS&A. Based on successful locking of the FS&A only, inspection to less than 100% might not be required for variables: **ah**, **axle**, **sls**, **bsh2**, **qang**, **rss**, **ax**, and **bx**. These eight variables may, however, contribute to other critical functions and for other reasons require 100% inspection.

CONCLUSIONS AND RECOMMENDATIONS

The predicated reliability of the fuze safe and arm (FS&A) mechanism is on the order of about 0.9999. This probability of success is consistent with the Excalibur's key performance parameter for reliability, 90%. To assure this FS&A performance, however, the following dimensions should be inspected 100%: **radius5**, **by**, **axle**, **rroter**, **qy**, **th3**, **ay**, and **rlI**.

If improvements to the estimated reliability are desired, the following changes should be considered:

- Dimensions: **axle**, **rroter**, **radius5**, **qy**, and **th3**; average dimension could increase; tolerances can remain the same
- Dimensions: **ay**, **rlI**; average value could decrease; tolerances can remain the same
- Dimensions **radius5**, **by**; average dimension can remain the same; tolerances could decrease

The extent of the changes would depend on cost and manufacturability of the individual parts. If dimensional changes are made, the reliability estimate should be revised. The extent of changes should also depend on the reliability of the FS&A functioning properly. Changing the dimensions to increase the Reliability to Safety may decrease the reliability of the FS&A arming correctly.

REFERENCES

1. Unipass, PredictionProbe, Inc., 3931 Mac Arthur Blvd., Suite 202, Newport Beach, CA 92660, 2003.
2. Kiureghian, A. D. and Liu, P-L., "Structural Reliability Under Incomplete Probability Information," Report No. UCB/SESM-85/-1, Division of Structural Engineering and Structural Mechanics, Department of Civil Engineering, University of California, Berkeley, January 1985.
3. Khalessi, M.R.; Wu, Y-T; Torng, T. Y, "Most - Probable-Point-Locus Reliability Method in Standard Normal Space," 9th Biennial ASME Conference on Reliability Stress Analysis and Failure Prevention, Miami, FL, 1991.
4. Lin, H.-Z. and Khalessi, M. R., "Identification of the Most-Probable-Point in Original Space-Applications to Structural Reliability," Proceedings of the 34th Structural Dynamics and Materials Conference, AIAA/ASME/ASCE/AHS/ASC, La Jolla, CA, pp/ 2791-2800, 1993.

DISTRIBUTION LIST

Commander
U.S. Army ARDEC
ATTN: AMSRD-AAR-EMK
 AMSRD-AAR-GC
 AMSRD-AAR-AEP-I (4)
 AMSRD-AAR-AEP-S (4)
 AMSRD-AAR-AEP-E (10)
Picatinny Arsenal, NJ 07806-5000

Defense Technical Information Center (DTIC)
ATTN: Accessions Division
8725 John J. Kingman Road, Ste 0944
Fort Belvoir, VA 22060-6218

Commander
Soldier and Biological/Chemical Command
ATTN: AMSSB-CII, Library
Aberdeen Proving Ground, MD 21010-5423

Director
U.S. Army Research Laboratory
ATTN: AMSRL-CI-LP, Technical Library
Bldg. 4600
Aberdeen Proving Ground, MD 21005-5066

Chief
Benet Weapons Laboratory, AETC
U.S. Army Research, Development and Engineering Command
Armament Research, Development and Engineering Center
ATTN: AMSRD-AAR-AEW
Watervliet, NY 12189-5000

Director
U.S. Army TRADOC Analysis Center-WSMR
ATTN: ATRC-WSS-R
White Sands Missile Range, NM 88002

Chemical Propulsion Information Agency
ATTN: Accessions
10630 Little Patuxent Parkway, Suite 202
Columbia, MD 21044-3204

GIDEP Operations Center
P.O. Box 8000
Corona, CA 91718-8000

Commander
Naval Surface Warfare Center
Dahlgren Division Code G06
Tech Library Code 323 (6)
Dahlgren, VA 22448