Testing for High Reliability: The 1% UXO limit on Cluster Munitions

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Outline

- **Statute and DoD Policy w/r/t Cluster Munitions**
- **Scoping the Tests:**
  - **Establishing Confidence**
  - **Exploring the "Operational Environments"**
- **Using all the data**
  - **Establishing confidence across the operational environments, without excessive producer risk**

Statute and DoD Policy

- Cluster Munitions Law:
  - (CONSOLIDATED APPROPRIATIONS ACT, 2012)

    Sec. 7054 (b) Public Law 112-74

    No assistance, licensing or technology transfer unless the submunitions have no more than 1% UXO across the range of intended operational environments.
- Origins in DoD Policy from 2008
- AT&L Guidance on Law and Policy issued 2014

2014 Guidance on Cluster Munitions

- Submunitions are UXO if unexploded, even if unarmed
- "across the range of intended operational environments" means in all environments, not an averaged measure
- "…a tailored test and evaluation approach is necessary to determine, *with reasonable confidence*…" that the 1% threshold is not exceeded.

emphasis added

What is “Reasonable Confidence”?

- Candidates include
  - point estimate
  - 80% (LRIP goals for reliability typically for 80% confidence of passing IOT&E for a system)
  - 90%
  - 95% common biomedical standard

  - We consider point estimate, 80% and 90%

Confidence calculation is straightforward

- For a fixed number, N, of submunitions, compute the probability that m will be UXO, for a true probability of 1%.
  - Exact binomial calculation is easy; texts frequently use a Gaussian approximation.
- The largest m such that the probability, P, is less than 1 minus the confidence level, C, is the upper limit for passing the test:

$$\max m \ \ni \ \ P < (1 - C)$$

For an submunition dispensing rocket

- Assume 504 submunitions per rocket;

Nominal Confidence Level Required	Maximum Number of UXO from 1 Rocket (504 submunitions)	Confidence Level Established*
Point estimate	5	39.1%
80%	2	88.0%
90%	1	96.2%

- For a single rocket test, establishing 1% with 80% confidence requires performing at 0.4%
  - Power is low, and consumer's risk is high

* This is the probability of exceeding the "Maximum Number" if the actual UXO rate were 1%.

Expand the test to increase power

- 9 Rockets, 4536 total submunitions;

Nominal Confidence Level Required	Maximum Number of UXO from 9 Rockets (4,536 submunitions)	Confidence Level Established
Point estimate	45	48.2%
80%	39	80.8%
90%	36	91.0%

- In this case, establishing 1% with 80% confidence requires performing at 0.86%.

Consumer's and Producer's risk

- Consumer's risk is minimized by insisting on confidence.
- Producer minimizes risk by designing in margin. In this case (4536 submuntions), a 0.75% true UXO probability results in a 17% chance of failing to meet the 1% with 80% confidence requirement.
  - Consumer and producer risk are comparable given a 25% design margin.

What do we mean by "across the range of intended operational environments"?

- Typically, for artillery systems testing explores range to target and carrier temperature.
  - Other factors can matter, but for this example we consider only range and temperature.
- 3 temperatures, hot, cold and ambient are typically considered.
- For this example, two ranges are considered
  - The primary effect of range is believed to be rocket velocity at time of dispersal, and this has a minimum at medium range.

What does a 2 factor, 6 condition test do?

- If all 6 conditions must have 39 or fewer UXO, a true UXO rate of 0.86% has a 2.5% chance of passing.
  - We are back to low power, high producer risk
- We need a way to determine if the factors matter: If the data from multiple conditions can be combined, producer's risk can be reduced, without increasing consumer's risk.

What if one or both factors don't matter?

Number of Rockets (submunitions)	Maximum Number of UXO from combined Rockets	Confidence Level Established	"Extra" UXO (Max - 39*Rocket number)
18 (9072)	82	80.6%	4
27 (13608)	125	81.8%	8
54 (27216)	257	81.4%	23

- The 1% limit on UXO can be established, with confidence, even if you exceed 39 UXO in some bins – if the data can be combined.

A proposal for using all the data

- Assume the true UXO probability (P) depends on temperature, T and Range, R, and can be described by the logistic regression.

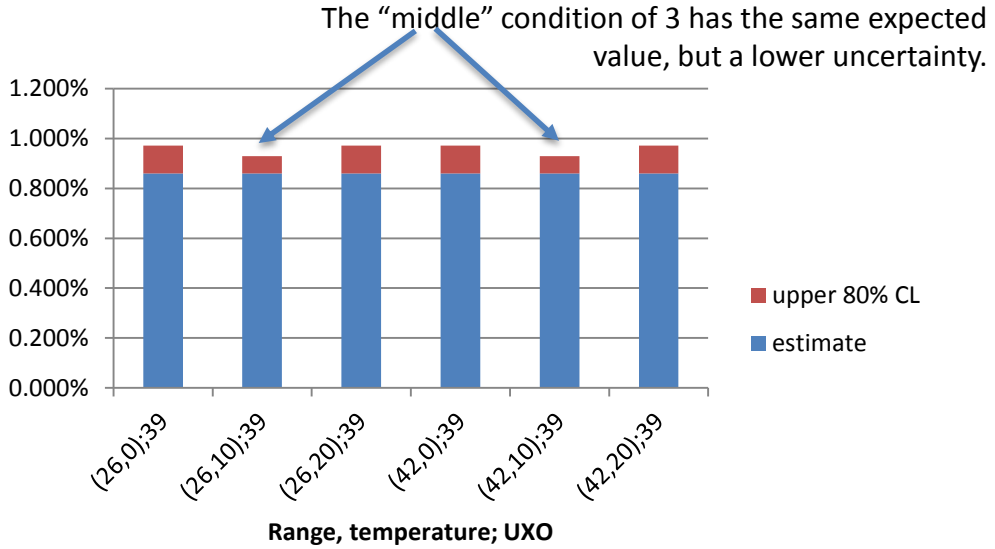
$$\left(\frac{P}{1-P}\right) = \exp(K + aT + bR + cTR)$$

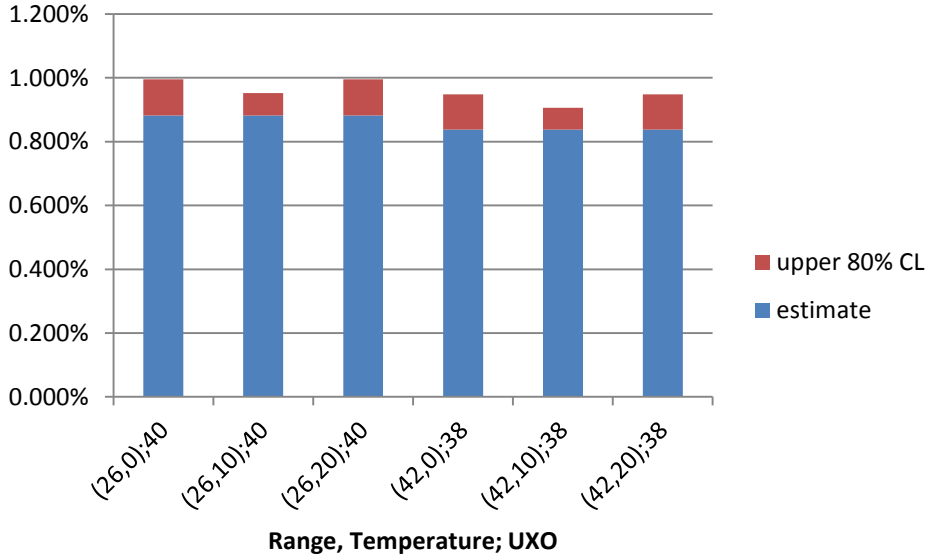
- *K,a,b,* and *c* are fit to the UXO number.
- This approach was implemented using JMP.

The logistic regression allows for some scatter

If there are 39 UXO in each bin (234 total), our estimate is 0.86% (remember that #?) and we have 80% confidence the UXO probability is ≤ 0.97%, or 0.93%, depending on the condition.

With a little scatter – e.g. the short range shots have 40 UXO and the long range 38, all have 80% confidence the UXO probability is ≤ 1.0 %. (Two of the 40 UXO cases barely.)

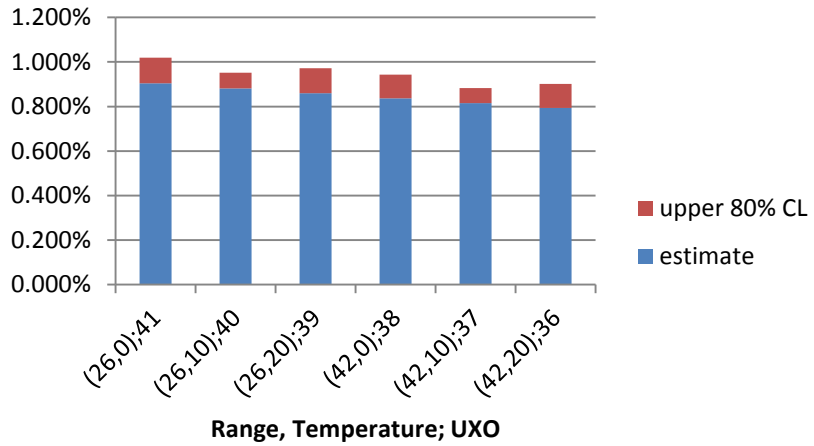




… but not if there is a "bias"

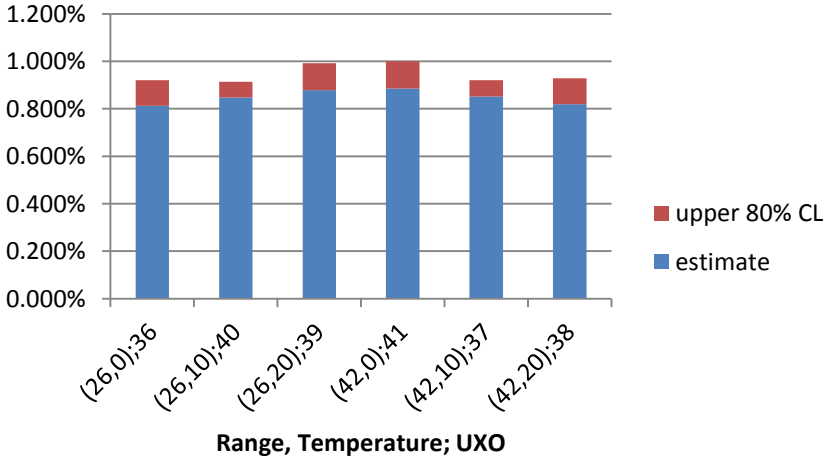
If the short range shots all have 3 more UXO than the same temperature long range shots, and each temperature step up decreases the UXO count by 1, the low range, low temperature shot (41 UXO) does not satisfy the 80% confidence criteria. (Note, there are 231 UXO total.)

Low range and low temperature are systematically worse, and there is not 80% confidence that the low-low condition has <1% UXO.



With no pattern to the failure distribution, all conditions establish <1% UXO with confidence. (A couple of cases barely.)

Below, the same 6 UXO numbers show no bias on either range or temperature, and everyone passes with 80% confidence.



With design margin, a smaller test works

- Notional example: A system dispensing 500 submunitions, with a 0.5% UXO probability.
  - We expect 2 or 3 UXO (47% combined probability)
  - 3 UXO fails to establish 80% confidence that the UXO rate is <1%, but the probability of 3 or more UXO (with a 0.5% true rate) is 46%.
- However, if we test across the operational environment, 6 bins, and can combine data, a test of one rocket per bin makes sense
- Examples follow

Submunitions with UXO probability = 0.5%

- Expected number per bin is 2.5 = 0.5%*500.
  - With 2 or 3 UXO per bin, we have 80% confidence the UXO rate is below 1%. (The 80% confidence limit is given in parentheses):

	T=0	T=10	T=20
R = 26 km	2 (0.69%)	2 (0.56%)	2 (0.69%)
R = 42 km	3 (0.93%)	3 (0.79%)	3 (0.93%)

  - With the same total number of UXO, but 1 or 4 per bin we get a different result:

	T=0	T=10	T=20
R = 26 km	1 (0.43%)	1 (0.32%)	1 (0.43%)
R = 42 km	4 (1.17%)	4 (1.02%)	4 (1.17%)

Summary

- The <1% UXO requirement for cluster munitions is established in Law and Policy.
- The limit must be established "with confidence" across the range of intended operational environments.
  - The confidence requirement limits consumer risk.
  - Producer risk can be limited by performance margin.
    - Testing has to be extensive enough to have low probability of a good system failing the test.
  - Data taken under multiple conditions (across the intended environments) should be combined, when valid.
    - Examples are presented using a logistic regression.
- Combining data also permits less extensive testing on systems with significant performance margin.

Questions?

Comments?

Backup

Sec 7054

(b) Cluster munitions. -No military assistance shall be furnished for cluster munitions, no defense export license for cluster munitions may be issued, and no cluster munitions or cluster munitions technology shall be sold or transferred unless-

(1) the submunitions of the cluster munitions, after arming, do not results in more than 1 percent unexploded ordnance across the range of intended operational environments; and …