Uses of Balloting Analyses During Projectile Development

Balloting analysis can help developers and producers of small, medium, and large caliber projectiles better understand the interaction between projectile and launch tube, helping to quantify both dispersion and targeting error budgets. The highly dynamic nature of projectile launch and available volume requirements for accelerometers typically precludes instrumentation of all but the largest of projectiles, leaving simulation as the only method by which these processes can be understood. Balloting characterization of a given projectile/gun tube combination can be accomplished quickly, giving the engineer insights on lateral accelerations, bending, angular rates, tube motion and tube pointing that would otherwise be impossible to capture, or excessively costly and time consuming.

Balloting Definition:
Balloting is the lateral motion of a projectile perpendicular to its longitudinal axis during in-bore travel. This motion can arise from any combination of a number of sources, among these are:

1. In-bore clearances between the projectile and bore (built in for medium & large caliber, pressure induced in small caliber).
2. Lack of perfect bore straightness (barrel bores are impossible to make perfectly straight, even in small caliber).
3. Gun tube centerline not coincident with center of gravity of the recoiling mass
4. Gun tube has externally applied mass (e.g. bore evacuator, muzzle brake, etc.) which bends the tube and modifies lateral reaction to internal pressurization and projectile in-bore motion.
5. Lack of projectile concentricity (manufacturing tolerances create slight, but important, offsets between a projectile geometric and mass center.

Why Balloting Analysis Reduces Development Risk:
While balloting accelerations are typically much smaller than the longitudinal acceleration, these lateral loads may grow to significant levels and cause excessive dispersion and/or structural damage to the projectile during in-bore travel. During projectile development it is advantageous to subject the projectile to an in-bore balloting analysis to determine:

- Expected dispersion and sensitivity to various projectile/cartridge parameters.
- Expected tube deflections during projectile passage and resulting projectile mean point of impact.
- Expected lateral accelerations, bending moments and durations.
- Effect of bore centerline deviations on dispersion.

All calibers and types of tube launched munitions can benefit from balloting analysis because a dispersion prediction will be made prior to committing the design to fabrication. In addition, if tube straightness measurements exist or can be simulated, the bending moments and lateral accelerations at key projectile axial locations can be evaluated. This information can then be compared to the structural strength of the projectile and the structural margin of the projectile subsequently assessed, providing the engineer with increased confidence that the projectile design can successfully survive the launch environment in at least some of the population of existing barrels. If tube straightness is unknown, a straightness profile can be assumed or scaled from available data.

The peak lateral accelerations seen by a projectile in a barrel with "worst case" straightness can be larger by a factor of 10-20 above those seen by an identical projectile in a barrel with a "benign" bore shape. The large increase in lateral accelerations that accompanies the "worst case" barrels greatly increases development and production risk for both guided and ballistic projectiles. The statistical nature of cartridge assemblies virtually assures that the balloting loads will vary shot-to-shot and barrel-to-barrel, contributing to seemingly random structural failures or dispersion "fliers".

Is Balloting Analysis Time Consuming?

Early in the history of balloting analysis, computer computation speeds were relatively slow and balloting simulations were quite time consuming. With today's computing speeds and storage capabilities, balloting simulations have become routine and a statistically meaningful simulation series can typically be completed in less than an hour, once the bullet and barrel models are completed and the boundary conditions have been identified. Sensitivity studies, e.g. bourrelet location, stiffness, bore curvature, etc., require several similar simulations in sequence, so times for adequate simulations to identify your particular problems depend upon user needs.

How is dispersion simulated via BALANS?

BALANS is an integrated part of Arrow Tech's Projectile, Rocket, Ordnance Design Analysis Software (PRODAS). As such, results from one analysis module are seamlessly passed through to subsequent analysis modules, making sophisticated trade studies quick, consistent, and accurate. Other than the projectile model, a model of the tube must be created, along with an understanding of where the tube is held by its mount, and the rigidity of these connections to ground. Wherever possible, actual measured physical data and forcing function (pressure-time history) are used in the analysis. This ensures accurate simulation of performance data acquired to date and allows for accurate prediction of expected long-term dispersion and targeting performance. This analysis technique is very powerful because it provides both dispersion and a targeting error budgets, with relative magnitudes of the error budget components for a particular projectile.

Figure 1 contains a flow diagram of this stochastic method for predicting dispersion. Whether trying to predict dispersion on a new design or solve a dispersion related problem on a current design, the approach is very similar. The analysis begins by gathering basic technical information such as manufacturing and assembly drawings and/or specifications. This information is critical to building an accurate analytical model of the projectile to be used during all analyses within this approach. From this information, a tolerance study is performed for inputs into the in-bore balloting analysis.

The second piece of information required for projectiles currently in production, is production history information, such as Statistical Process Control (SPC) data. Even if working with a new projectile design for which there is no production history, it is valuable to obtain this information for a similar design or a projectile with similar characteristics. Since some of the inputs to this approach are statistical in nature, the historical data provides a foundation from which to derive the statistical information. If no production dimensional information is available, it is assumed the “average” projectile is built to the mean of the dimensional tolerance, and that the limits represent plus or minus 3 standard deviations from the mean. Statistical variability of the pressure-time forcing function can also be included in the balloting analyses, improving the fidelity of the dynamic system simulations.

The last type of information required is test and/or measurement data that is important to predicting dispersion but are not necessarily derived from analysis. This includes bore centerline measurements, bore site errors inherent within a test fixture or bore site tool, known sabot discard issues from tests of similar sabots, etc.

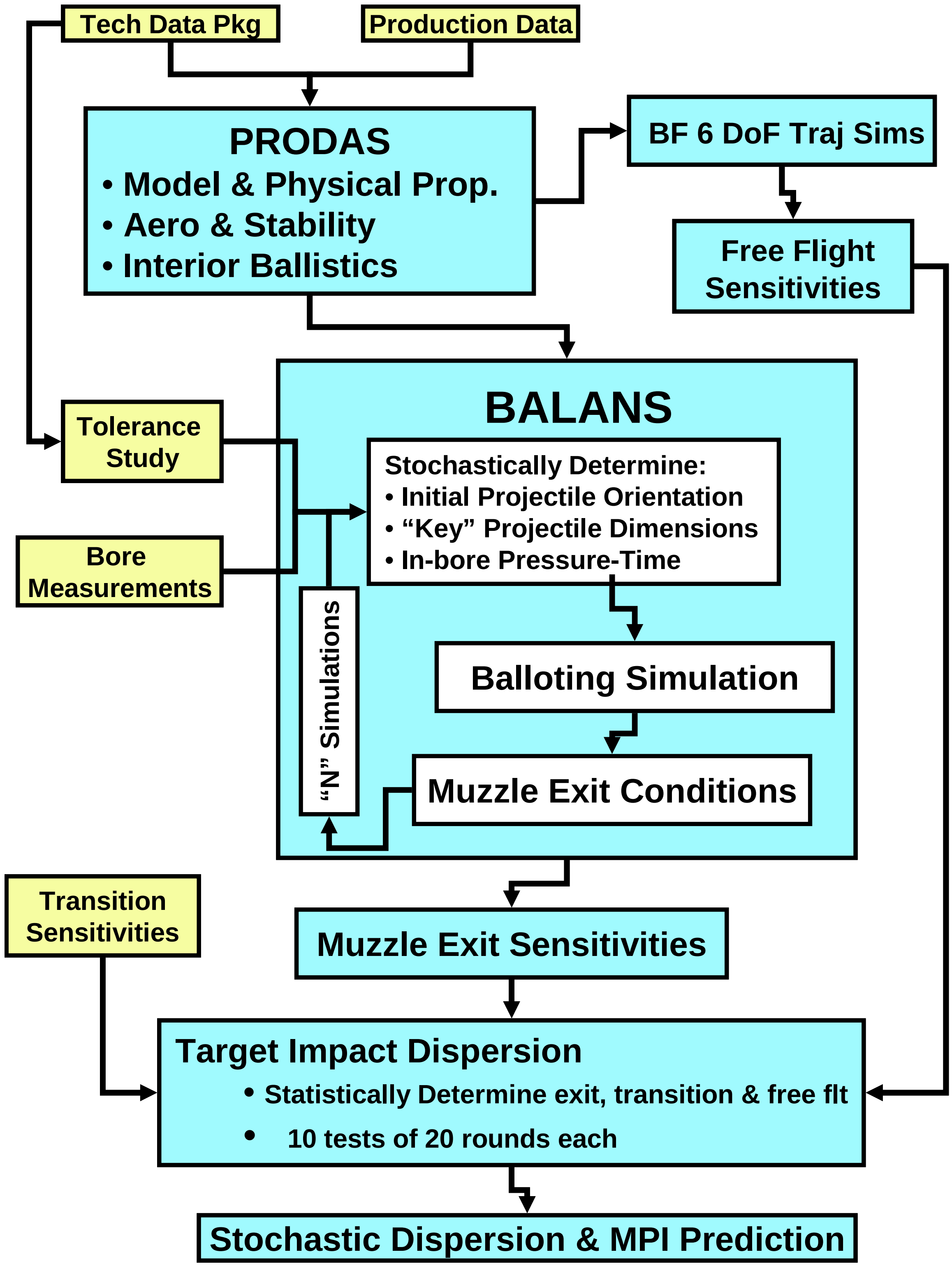

Figure 1: BALANS Dispersion Analysis

As can be seen in Figure 1, the drawings and production history are used for physical modeling of the projectile which in turn provides the basis for several analyses to be described in the following sections. Each of the analyses results in various dispersion component sensitivity information, which is used in predicting dispersion. Comparison of predicted dispersion with test data is important because it provides a "sanity check" for the analytical portion of the analysis.

Why use a stochastic approach for selection of initial conditions?
The question is sometimes asked: "Why is a stochastic approach needed when only one, at most, a handful of projectiles is launched at a time?". The balloting results shown Figure 2 illustrates why a stochastic approach to balloting analysis is essential to obtaining an accurate representation of the in-bore environment.

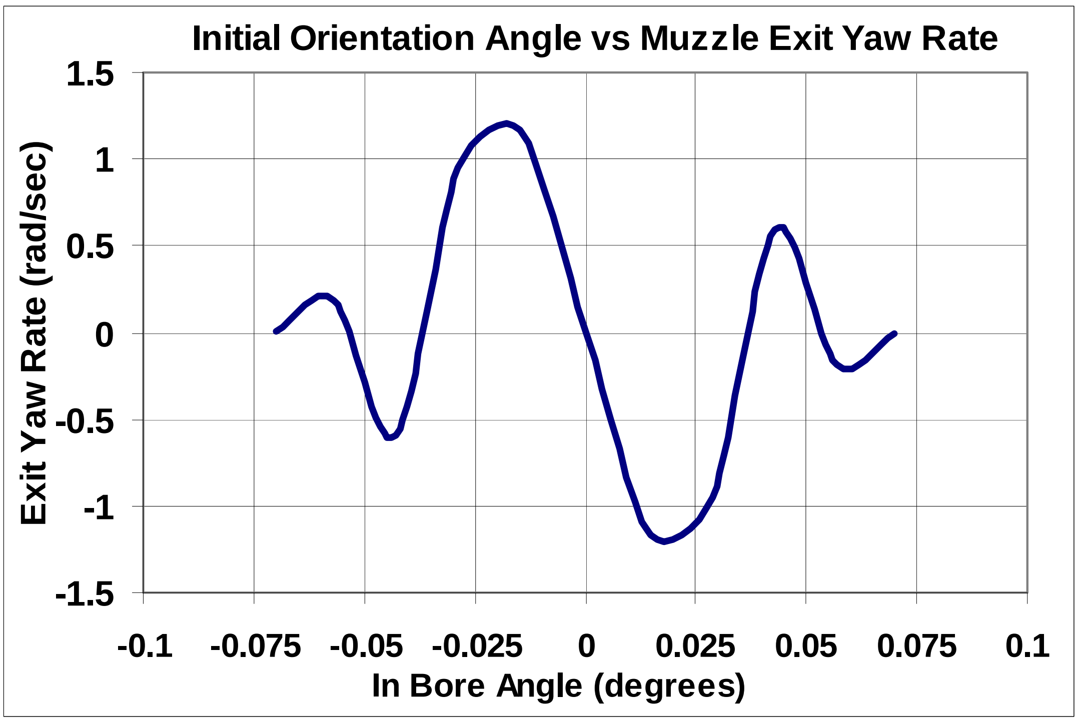

Figure 2: Exit Yaw Rate vs. Initial Orientation

Since the initial angle required to yield the maximum exit yaw rate is neither the maximum angle, nor zero, nor the average of the two, it is clear that selection of the initial angle resulting in maximum angular rate at exit can only be obtained by random selection. ***Representative exit conditions can only by obtained by selecting initial conditions using a stochastic methodology.***

Projectiles launched from high performance gun systems are sensitive to small variations in initial conditions, bore straightness, and/or applied forcing function. While it is true that high performance projectiles are fabricated with remarkable precision, the center of mass of the projectile assembly is almost never perfectly aligned with the geometric center of the projectile. Assembly of the piece parts and/or manufacture of any projectile is also imperfect (dimensional and run out tolerances). These small differences of the mass axis have an alignment with the geometric axis that is not predictable, and may be difficult or impossible to measure. While small caliber projectiles differ from medium and large caliber projectiles in that their bourrelets are an interference fit with the barrel lands, the use of stochastic methodology to select the initial conditions for this class of projectiles is still appropriate due to the random orientation of the projectile axis tilt relative to the bore centerline, and a small bore diameter increase caused by chamber pressure behind the projectile after initial engraving, and the likelihood that the plane of in-bore angle of projectile tilt will be oriented randomly shot-to-shot. Small differences in initial orientation, and the projectile mass axis offsets, when combined with the bumps in the gun tube (due to lack of straightness) produce different maximum stress conditions for each projectile fired, along with variable angular rates and cross velocity on every shot.

Forcing function (pressure-time history behind the projectile) variability is an example of boundary conditions that can interact with the projectile and gun tube bore centerline curvature to cause increased dispersion and/or a mean point of impact shift. Balloting simulations can determine the magnitude of mean point of impact shift that would be expected to occur with the large temperature variations between standard military hot, cold and ambient ammunition conditioning, or the increase in dispersion from within lot changes in peak pressure, muzzle velocity or action time at a given temperature. Since the balloting code is constructed to allow the user to import the desired forcing function mean and representative standard deviations, the effect of peak pressure, muzzle velocity, and action time deviations on dispersion and expected impact point can be assessed. The interaction of ammunition pressure-time variability with (lack of) bore straightness poses some challenging engineering and production issues for single barrel gun systems with changeable barrels that have an impact point retention requirement, or systems firing ammunition with dramatically different in bore mass (e.g. full caliber vs. saboted ammunition) with a requirement to shoot to the same impact point within a certain angular error. Balloting simulation reduces development and production risk by enabling the program manager to understand the effect of uncontrollable variables on system performance prior to committing the design to production.

Why use BALANS to determine Lateral Accelerations and Bending Moments?

Using the balloting analysis, the in-bore environment seen by the projectile can be more completely understood. This helps engineers design the projectile to withstand actual expected environments at some confidence level, not the maximum allowed by drawing. This is an important advantage of using the balloting simulation, as structural over-design can be nearly as limiting as is the failure to understand the existence of the lateral acceleration environment. However, while it is important to select and measure a representative sample of bore profiles, **accurate assessment of the projectile in-bore environment can only by obtained by selecting initial conditions using a stochastic methodology. Attempts to measure the in-bore environment via on-board telemetry suffer severely from high cost and small sample size (number of projectiles, initial conditions, and bore profiles, etc.).**

Arrow Tech has performed balloting analyses on numerous projectiles to assess the magnitude of the mean and standard deviation of lateral acceleration and bending moments. To do this, a measurement or estimate of the barrel bore centerline straightness must be made. Whenever possible, multiple samplings of representative bores should be taken and compared statistically to provide the customer with increased confidence that the sampled tubes are representative of the whole population of tubes.

In a recent balloting analysis, the centerlines of about 10 tubes were provided. Figure 3 shows bore centerline deviation in the "Y" plane of the best tube of the population, and "average" tube and two tubes that were determined to be "worst" by two different evaluation criteria. The "worst" tubes were selected based on (lack of) straightness over the whole bore length and on a running interval measurement criteria.

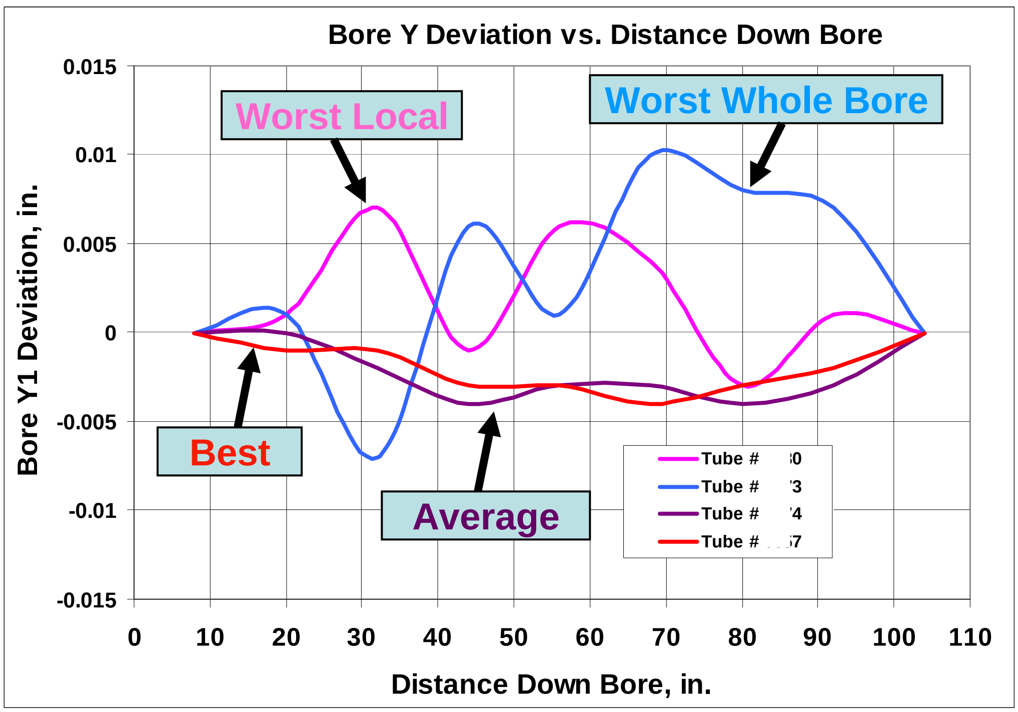

Figure 3: Measured Bore Centerline Profiles

By statistical analysis of the whole population of bore profiles sent, it was determined that the "worst whole bore" profile represented a bore deviation that would include 95% of all barrels made, assuming the provided sample was representative of the whole barrel population.

Using the two "worst case" barrels, the lateral accelerations caused by this bore profile was assessed. The mean and standard deviation in RSS lateral accelerations caused by travel down these two barrels is displayed in Figure 4.

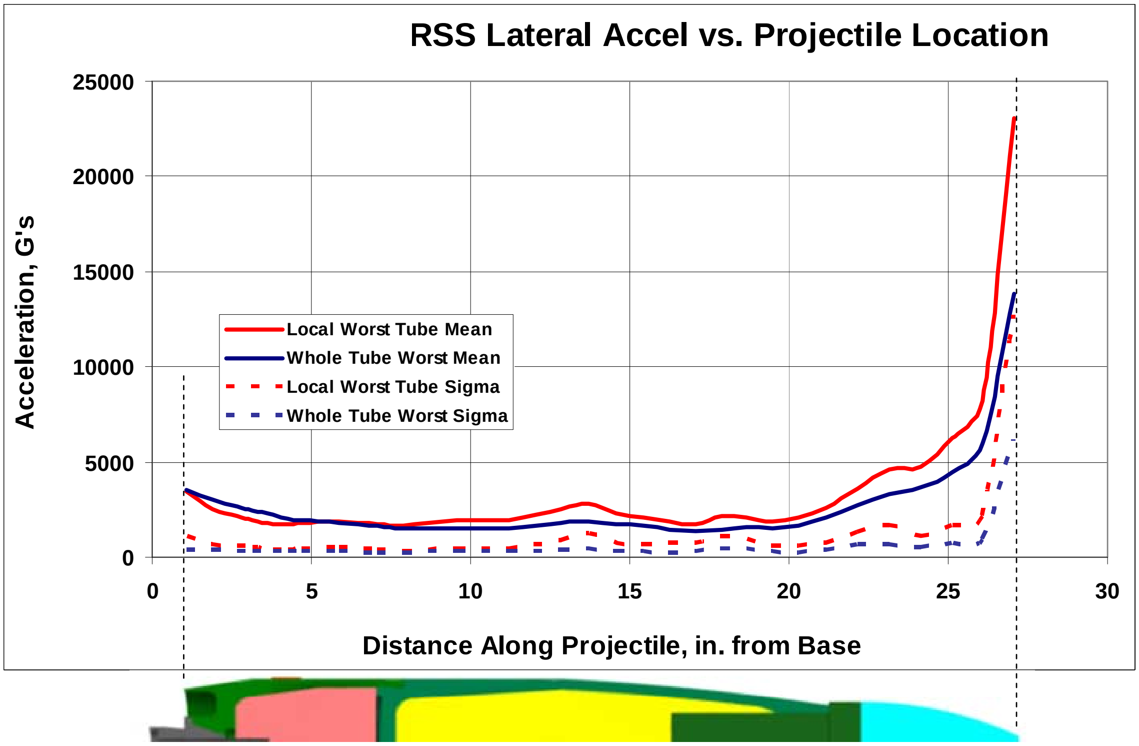

Figure 4: RSS Lateral Acceleration Mean & Sigma vs. Projectile Location

Figure 4, the mean and standard deviation in RSS lateral accelerations are fairly benign at the aft end of the projectile and increase significantly near the front end of the projectile. Components within the projectile near the tip of the ogive must be designed to withstand these accelerations if the projectile is to survive launch in these barrels. This includes mechanical components (e.g. fuze mechanism(s), structure, etc.) as well as electronic components, if applicable.

The mean and standard deviation of the bending moments generated by firing in these two barrels are shown in Figure 5.

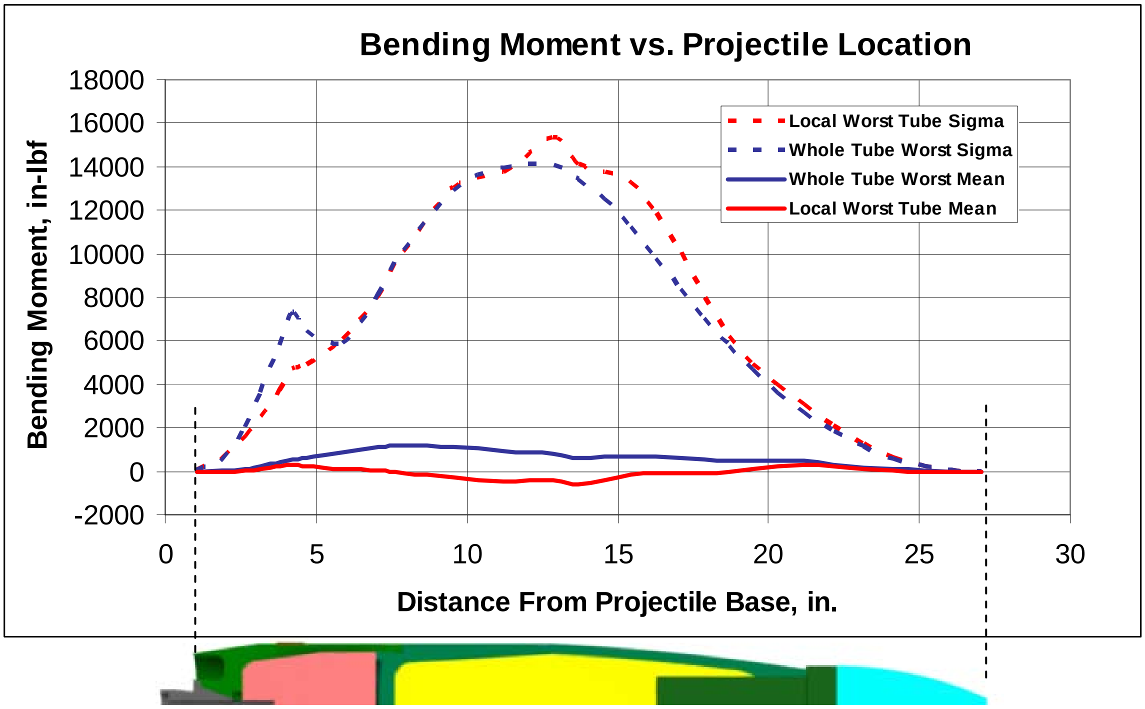

Figure 5: Bending Moment Mean and Sigma vs. Projectile Location

Figure 5 shows the anticipated mean and standard deviation in bending moment at various locations along the projectile, with the largest variation (sigma) appearing at the forward bourrelet for both barrels. This is not surprising as the projectile is modeled with a “gap” spring at the forward bourrelet and a significant portion of the projectile’s inertia forward of there would be reacted at this location.

With a stochastic approach to projectile initial conditions, in a tube representing the “worst case” of a population sample of barrel bores, an improved understanding of the lateral accelerations, bending moments and load durations imparted to the projectile during passage down the bore can be obtained. The time required to conduct these analyses is limited primarily by acquisition of input data (e.g. pressure time history, bore straightness, SPC data on projectile dimensions, etc.), not actual “number crunching”. Balloting analysis can provide significant insights into the ability of the projectile and sensitive components to withstand the launch environment.

With measured bore centerline information, the Mean Point of Impact (MPI) of specific projectiles fired from a barrel can be estimated. A comparison of estimated barrel MPI’s can be useful if the system in which the barrels will be used has a requirement for boresite retention after barrel change, or if the gun has multiple barrels which have a requirement to place projectiles in close proximity to one another.

Action time variability interacting with bore curvature is a potential ammunition dispersion source that can be evaluated with BALANS for projectile / barrel systems of interest, provided the effect on interior ballistic forcing function is known. Changes in pressure rise rate and velocity vs. travel shot-to-shot affect the barrel pointing vector for each shot and can increase the dispersion exhibited by the ammunition.

Background on Balloting & Dispersion Prediction via Numerical Simulation

The ability to predict the dispersion of a projectile is challenging because dispersion is a combination of independent and interdependent random “events”. There are many parameters that influence these “events”. The analysis is even more challenging if the intent is to provide assurance that a projectile design, as manufactured, will consistently pass the Target Impact Dispersion (TID) Lot Acceptance Test (LAT) requirement since this requires the incorporation of manufacturing limits and standard deviations.

Dispersion is normally computed and evaluated based on testing during the projectile development phase; however, this is very time consuming and expensive. When tests are performed, it is unlikely that sufficient testing is performed to provide assurance that dispersion requirements will be met across the total range of tolerances for every part/assembly.

One of the primary contributors to the in-bore balloting component of dispersion is the accumulation of tolerances in the manufactured projectile parts and assembly of those parts into a projectile with a CG that does not lie on the geometric center of the projectile. With high velocity, conventional guns, very small CG offsets can produce catastrophic results. While a user may want to know what the worst possible launch scenario may be, he/she may also be interested in the likelihood of a failure occurring. Use of a stochastic approach enables the analyst to determine the probability of acceptance failure due to either structural or launch induced dispersion phenomena. It also gives the user the range and mean of expected behavior.

Selection of a "worst case" analysis condition typically requires several trial and error analysis replications because the relationship between maximum balloting loads and the initial orientation of projectile CG offset and principal axis tilt is not linear. An analytical procedure set up to only run one set of conditions at a time is of limited value in this regard and can prove very time consuming. It has been Arrow Tech's experience that an approach that randomly selects initial conditions and continues with a sound analytical solution can prove very useful in determining the probability of occurrence of the outcome.

Balloting History:
Arrow Tech has used BALANS to analyze the expected dispersion behavior of a number of projectiles. A partial list of the projectiles analyzed via this technique is shown in Table 1.

Caliber	Projectile	Year
5.56mm	M855 Green Ammo	2004 2007
7.62mm	M80 Copper M80, M118, Copper	2001 2008 2010
9mm	Marker	2010
20mm	Mk149/Mk244	2004-10
25mm	M791/M910	1991
	M919	1994
	XM1019/XM1049	2004
30mm	PGU-14/B	1973
	Long Rod	1999
39mm	Long Rod	2008
40mm	PGU-31	1992
	ALACV	2001
45mm	COMVAT	1990
50mm	EAPS	2007
60mm	N/L Mortar	2004
81mm	N/L Mortar	2002
90mm	"SLEKE" EM Projectile	1990
	M697	2002
105mm	M735	1979
	M774/M833	1980
	M9XX	1982-84
	M900	1988-89
	M1060A2	2002
	APS Rocket	2008
	M913	2008
115mm	APFSDS-T	2010
5 Inch	Mk82/Mk172	2001
120mm	M829A1	1986
	M865	1987
	M865SS	1987
	FMS-KET	1987-88
	M829A1	1987-89
	M829	1988-89
	M829E2	1989-91
	M865SS	1990
	M831A1	1994
	M865SS	1994
	M934	1997
	M865SS	1998
	M829E3	1995-2005
	M1002	2006
155mm	LRLAP	2005
	M864	2007
	CLGG	2007-2008
	Guided	2009

Table 1: 5.56mm-155mm Balloting Analyses & Years

The work shown in Table 1 was conducted for the following customers:

- ARDEC
- ARL
- ARMTEC
- ATK
- BAE
- Barnes Bullets
- Eglin ARF
- GDATP
- GDOS
- GD-OTS
- GE
- Goodrich
- Honeywell
- Lewis Machine Tools
- MECAR
- NSWCDD
- Picatinny Arsenal
- PRIMEX
- SAIC
- UTRON

The 30mm PGU 14-B entry shown in Table 1 in red was the genesis of the balloting code known as BALANS. Figure 6 show a flash X-ray taken just after muzzle exit of a developmental PGU-14 API projectile.

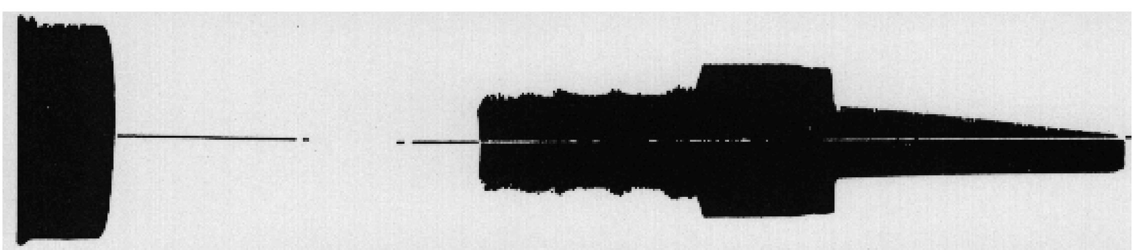

Figure 6: 30mm PGU-14 API Elastic Deflection at Muzzle Exit

BALANS was used to understand the elastic core bending, which was the source of the excessive dispersion exhibited by early versions of GAU-8 API ammunition.