CHARACTERIZATION OF BALLISTIC IMPACT FLASH: AN INITIAL INVESTIGATION AND METHODS DEVELOPMENT

GRADUATE RESEARCH PAPER

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AFIT/IOA/ENS/10-04

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Abstract

Ballistic impact flash plays a pivotal role in the ignition of fires in military vehicles. Flash duration, geometry, and energy profiles are critical variables in the assessment of ballistic-induced fires. The survivability community has identified a need for a standardized data collection methodology and corresponding valid community verified models. This effort will quantify existing test data and begin the process of producing dynamic models for flash geometry based on projectile and target material properties and impact conditions.

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To My Family

Acknowledgments

Special thanks go to my research advisor, Dr. Raymond Hill, for his untiring mentorship and guidance during this program of study. Without his help and understanding, this research project would have never been completed.

Thanks also to the Aerospace Survivability Flight of the 46th Test Group, OL-AC, at Wright-Patterson AFB. In sponsoring this research project, they allowed me to expand my education through practical application. I hope that my efforts will prove of value to current and future Americans in harm's way.

Todd Henninger

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CHARACTERIZATION OF BALLISTIC IMPACT FLASH: AN INITIAL INVESTIGATION AND METHODS DEVELOPMENT

I. Introduction

Background

Ballistic impact flash is caused by a projectile impacting an object at high speed. In this study, the projectiles are similar to fragments from an exploding warhead, and the object being impacted is similar to the skin of an aircraft or ground vehicle. These resulting flashes play a pivotal role in the ignition of fires in military vehicles.

The Aerospace Survivability and Safety Operating Location (46^{th} TG/OL-AC) at Wright-Patterson AFB has sought to standardize data collection methodology and to develop valid flash characterization models. Current models were developed before the availability of digital high-speed video, and can only roughly predict flash duration and size. A new model should be capable of predicting flash shape, position, size, orientation, and thermal energy for the duration of the event.

This effort focused on developing models to predict flash size. Using data from multiple test shots performed by the 46^{th} TG/OL-AC, a regression analysis was performed and an empirical model was derived (Bestard & Kocher, 2010).

Problem Statement

This effort will help define empirical models for characterizing fragment flash from ballistic impacts for both Air Force and joint survivability analyses. The analysis includes initial verification of the modeling approach and insights into test design factors influencing resultant flash realizations.

Methodology

Using high speed camera information, flash information was generated for a set of operational experiments. These experiments varied fragment size, speed, and impact angle against various material types. Data analysis derived flash position, dimensions, and size as a function of time, both for the entry side of the test material coupon and for the exit side. This current effort focuses on building and verifying an empirical model of flash size radii, in both the horizontal (x-axis) and vertical (y-axis) planes. These models are regression-based using radius information as the response and time as the regressor.

Assumptions and Limitations

Key assumptions in this effort include:

- Data provided adequately reflects operational tests conducted;
- Tests are conducted with sufficient controls that design settings accurately reflect actual settings;
- The horizontal and vertical radii data are time series and can be adequately modeled as a time series.

This research is limited in some aspects to include:

- Since this is an initial effort, the research focuses on a specific subset of data with the express purpose of defining a methodology for flash characterization modeling;
- This effort will only examine the time-based characterization of the flash radii, either entry side or exit side (or both);

- Separate models for x-axis and y-axis radii are reasonable
- This research only focuses on flash size and not the thermal aspects of the flash.

II. Literature Review

This chapter provides a broad survey of projectile impact effect characterization studies to date. While many studies were accomplished in the 1960s-1980s, the most recent works found were four AFIT theses during the 1991-1993 timeframe.

Introduction

Aircraft combat survivability has been defined as the capability of an aircraft to avoid or withstand a man-made hostile environment. Survivability analysis covers a broad range of issues such an aircraft's radar and infrared signature, how easy it is to visually acquire the aircraft, aircraft speed, aircraft design, tactics employed, countermeasures available, aircraft armor, etc. These areas of concern involve detailed analysis of the many variables affecting the outcome of encounters with threats to the aircraft (Ball, 2003).

Whether or not an aircraft survives an encounter with a threat depends upon both the susceptibility of the aircraft (the aircraft must be hit in order to be killed) and the vulnerability of the aircraft (the hit must cause enough damage to kill the aircraft) (Ball, 2003). Examining ballistic impact flash assumes that the aircraft has been hit, and therefore falls into the vulnerability category. A main concern is the possibility of a flash igniting the aircraft fuel source, thereby causing fire and/or explosion. For this reason, an accurate predictive flash model is highly desirable for use in combat survivability analysis.

Reynolds (1991)

Reynolds focused on modeling the incendiary functioning (IF) of Soviet armor piercing incendiary (API) projectiles impacting graphite/epoxy composite panels. Until his effort, most studies had concentrated on targets made of metal. He used multivariate analysis and response surface methodology approaches, and uncovered a negative correlation between projectile residual mass and incendiary functioning (Reynolds, 1991).

Historically, most vulnerability assessments prior to Reynolds' thesis relied on a government study from the 1960s called Project THOR. This study revealed that target material and projectile characteristics (weight, speed, angle, etc.) were both important factors in determining projectile penetration. Project THOR, however, did not examine incendiary or high-explosive effects (Reynolds, 1991).

The *Penetration Equations Handbook for Kinetic-Energy Penetrators*, published by the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME), used the results from Project THOR and presented extensive data and equations to determine whether or not an API round will function given a specific target material. The handbook breaks down the prediction of incendiary functioning into five categories: incendiary fails to function, functions completely, partially functions, slow-burns, or has a delayed function. For projectiles other than those tested, there are correction factors that can be applied to the equations. However, these data and other models are not accurate for targets made of composite materials (Reynolds, 1991).

Reynolds' studied data from a test effort using the Soviet 12.7mm API round fired at different angles against various composite material thicknesses. The API round is designed to allow the outer jacket over the nose to peel away during impact, thereby igniting the incendiary material in the nose. The heavy steel (or other metal) core of the round then continues on its path. Ideally, the API round is capable of penetrating the skin of an aircraft, with the core subsequently rupturing fuel or hydraulic lines or fuel tanks, at which point a proper incendiary flash created upon initial impact with the skin would cause ignition of those escaping fluids (Reynolds, 1991).

In the analysis Reynolds used four predictor variables: impact velocity (IV), impact mass (IM), ply thickness (PLY), and impact obliquity angle (ANG) (Reynolds, 1991). These variables were used to derive formulas for residual mass (RM), residual velocity (RV), and incendiary function (IF).

Reynolds' data included some test shots where the incendiary function occurred on the entry side of the target. The analysis derived two separate regression models: one (type I) that classified entry-side functioning as actual functioning that could ignite fuel, and another (type II) that classified it as a non-function. The equations are listed below.

The discriminant analysis called for rounding of the results from the above equations, which yielded values that fell into the following five IF categories:

0 – No Function

1 – Delayed Function

3 – Slow Burn

4 – Partial Function

5 – Complete Function

Reynolds' effort improved upon the JTCG/ME with respect to composite targets, but left room for improvement in predicting what type of incendiary functioning will occur (Reynolds, 1991).

Knight (1992)

Knight (1992) expanded Reynolds' effort and continued to analyze API projectile function. Knight specifically used regression analysis, discriminant analysis, and neural networks to better predict residual velocity, residual mass, and incendiary functioning of 12.7mm and 14.5mm API rounds on graphite/epoxy composite panels (Knight, 1992).

Knight's test shots were accomplished by the Wright Laboratories Survivability Enhancement Branch. For incendiary functioning, 281 shots were valid. High-speed flash photography was used to document IF (Knight, 1992).

Knight created three separate IF classification cases: Case #1 – 2-group classification (nonfunctioning and functioning), Case #2 – 2-group classification (nonfunction (entry-side functions included) and mixed), and Case #3 – 3-group classification (entry-side, nonfunctions, and mixed). The mixed category included complete, delayed, slow burn, and partial functioning shots (Knight, 1992).

To summarize Knight's findings, a neural network algorithm was chosen as the best method to classify each shot into one of three categories: frontal (entry side function), mixed functioning (includes all types of function), and nonfunctions. The misclassification rate was 8.25%.

Lanning (1993)

Lanning (1993) studied API projectile effects when penetrating two composite panels. IF was examined only in that it directly relates to residual projectile mass. He states that incendiary effects are “not a quantifiable variable.” (Lanning, 1993) The technology available at the time to record the incendiary flash made it an inexact science. At the time, seven IF categories were used: non-function, partial, slow burn, frontal, delayed, and complete.

Using two panels expanded the possible results since each panel could see a different IF category. Since Lanning only had 52 data points, the number of IF categories was reduced to two. This made incendiary function a binary, yes or no variable. Discriminant analysis and neural networks were used, with promising results. Generally, it was found that composite panels require a higher projectile velocity in order to produce flashes, and that they produce flashes of a longer duration than aluminum panels (Lanning, 1993).

Blythe (1993)

Blythe attempted to establish a methodology for predicting flash characteristics of projectile impacts with composite materials, along with residual mass and velocity (Blythe, 1993).

Blythe highlights that exit-side flashes had not been studied much prior to that time. He mentions studies by Ritter in 1986 and 1989 of steel fragments impacting metal and graphite/epoxy targets that focused on flash duration, temperature, and pressure. Also highlighted was the current method for predicting the probability of kill for kinetic projectiles, which was the Computation of Vulnerable Areas and Repair Times (COVART) computer model (Blythe, 1993).

The test shots used 20mm and 30mm guns which shot the steel fragments into aluminum and composite targets. Exit-side flashes were first observed with mid-velocity shots (7,000 feet/second) for the aluminum target and not until the high-velocity shots for the composite (10,000 feet/second). Additionally, the flash peaked much more quickly with the aluminum target (0.2 milliseconds) than with the composite target (1.1 milliseconds) (Blythe, 1993).

While no model for predicting exit-side flashes was produced, Blythe recommended focusing on the 7,000-9,000 feet/seconds regime for composites, and using discriminant analysis for developing the prediction model (Blythe, 1993).

Summary

Past efforts focused on predicting residual mass, residual velocity, and a concept called incendiary function based on test characteristics of impact velocity, impact mass, material (ply) thickness, and angle of attack (obliquity). Those efforts were somewhat hampered by the video technology required to obtain the data. These same limitations hampered efforts to model flash size.

Current technologies are sufficient to obtain the requisite data. Thus, while the current data set allows re-examination of these past studies, the current effort is focused on building predictive models of flash size. The next section provides an initial approach along with model validation approaches.

III. Methodology

Data Collection

The data for this study was gathered by the 46th TG/OL-AC during 2009 in a series of approximately 500 experimental test shots taken on a firing range at Wright-Patterson AFB. In these experiments, the following inputs were varied: projectile weight, projectile velocity, target panel thickness, target panel weight, and impact obliquity. Digital high-speed video was taken and subsequently analyzed for each shot.

The 46th TG/OL-AC then used automated data reduction techniques to examine impact video, and impact flashes were characterized and surrounded using ellipses. Measures on the ellipses provide flash size data. A numerically stable method, based on least squares minimization, was used that was able to handle the noisy data nature of the flash (Bestard & Kocher, 2010). This method produced usable time sequenced data for ellipse centerpoint, ellipse radius, ellipse orientation, and ellipse area. A video frame with entry (right) side and exit (left) side flashes with fitted ellipses is shown in Figure 1.

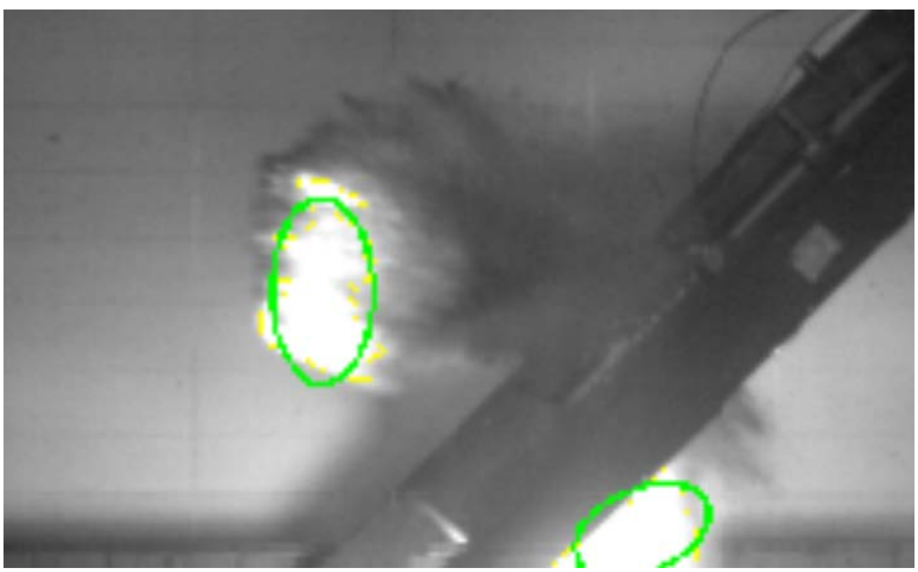

Figure 1. Video Frame with Entry and Exit Flashes and Fitted Ellipses

Details of the impact flash measurement method are found in Bestard and Kocher (2010).

Initial Investigation

Test data for 72 shots of steel fragments against bismaleimide resin (BMI) targets were examined. For this regression analysis, shots were examined and grouped into those replicates that had the most data points. These shots were plotted with flash radius (for both x and y axes) against time. Eight shots were selected for further investigation all of which appeared to have sufficient data. These shots appear in Table 1, and include four shots with two replicates each.

Table 1. Test Shot Data used in Study

Test Number	Date	Projectile	Velocity	Target Panel Thickness (in)	Obliquity
T011	1/8/2009	75gr	7000	0.1	45°
T012	1/13/2009	75gr	7000	0.1	45°
T031	1/16/2009	75gr	5500	0.35	45°
T032	1/16/2009	75gr	5500	0.35	45°
T033	1/16/2009	40gr	7000	0.35	45°
T034	1/16/2009	40gr	7000	0.35	45°
T035A	1/16/2009	75gr	7000	0.35	45°
T036	1/16/2009	75gr	7000	0.35	45°

A sample of the data from a test shot is shown in Figure 2. Partial Data Set for One Test Shot. The “rx_1 (m)” and “ry_1 (m)” represent x-axis and y-axis radius data, in meters, respectively. These shots were plotted with flash radius (for both x and y axes) against time. A sample plot associated with a different test shot is shown in Figure 3.

Time (s)	rx_1 (m)	ry_1 (m)
2.10E-05	0.049387	0.03115
4.20E-05	0.1056	0.044159
6.30E-05	0.06884	0.039
8.40E-05	0.062244	0.031602
0.000105	0.055796	0.025628
0.000126	0.049989	0.023893

Figure 2. Partial Data Set for One Test Shot

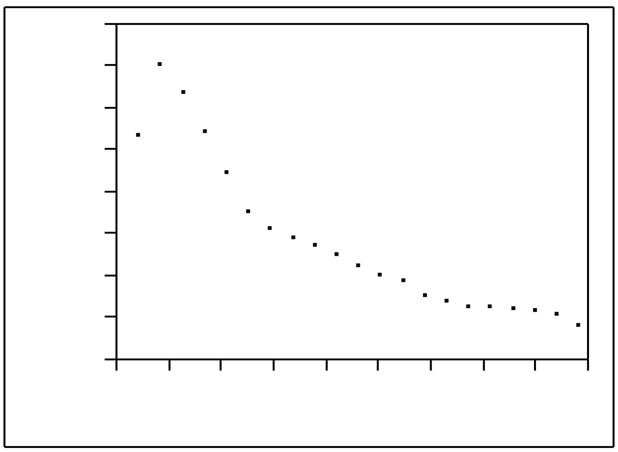

Figure 3. Flash Radius versus Time (x-axis radius only)

In general there was more data for entry-side impact flashes than for exit-side. This may have been due to the fact that the shots in this data set with enough data points were all at 45 degree obliquity and 7000 feet per second or less. Therefore, entry side flashes were the focus of this effort.

Figure 4 through Figure 11 are time series plots of the horizontal (x-axis: rx) and vertical (y-axis:ry) radii data for the selected shots of interest. The initial goal is to characterize each time series (rx and ry) at sufficient fidelity to simulate the flash events. This characterization requires some deterministic component coupled with a random element (error). If we assume the error are normally distributed, the characterization takes on the form

What remains is to build f(time) and determine .

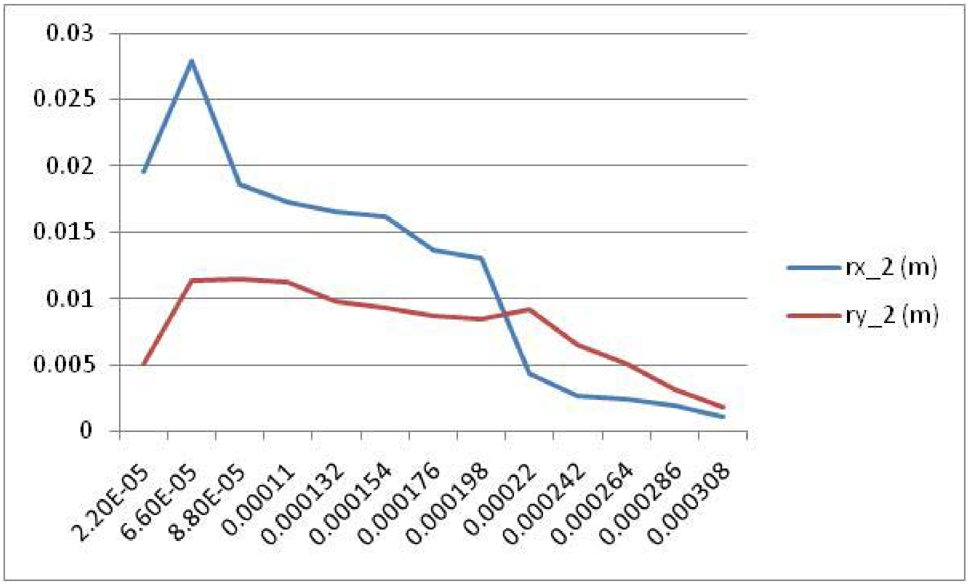

Figure 4. Shot 11 Radii vs. Time

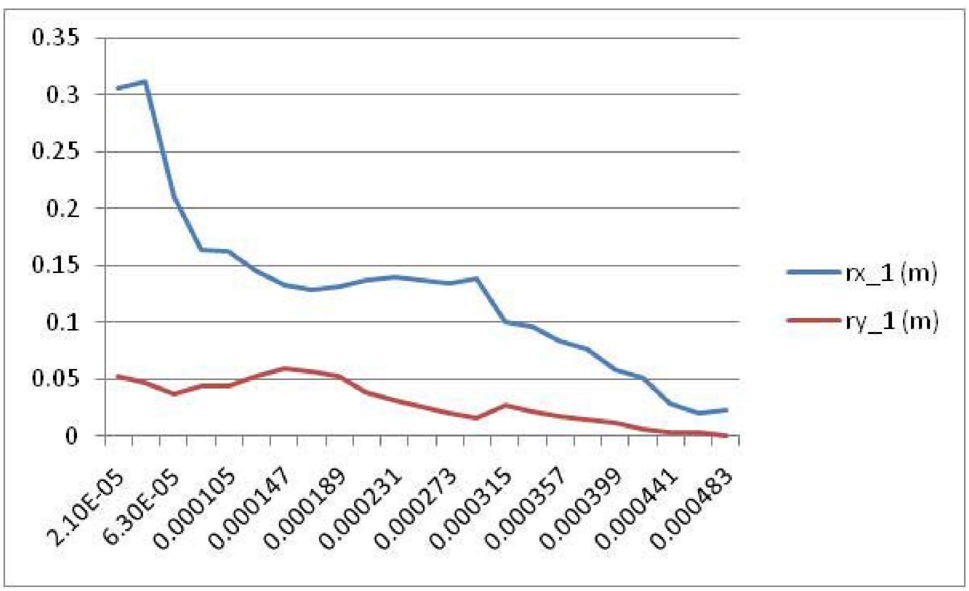

Figure 5. Shot 12 Radii vs. Time

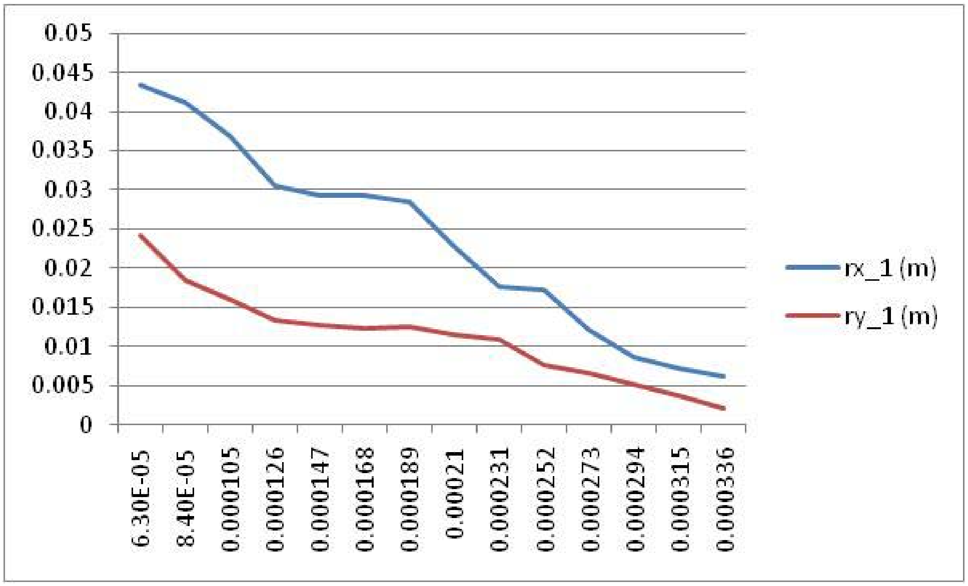

Figure 6. Shot 31 Radii vs. Time

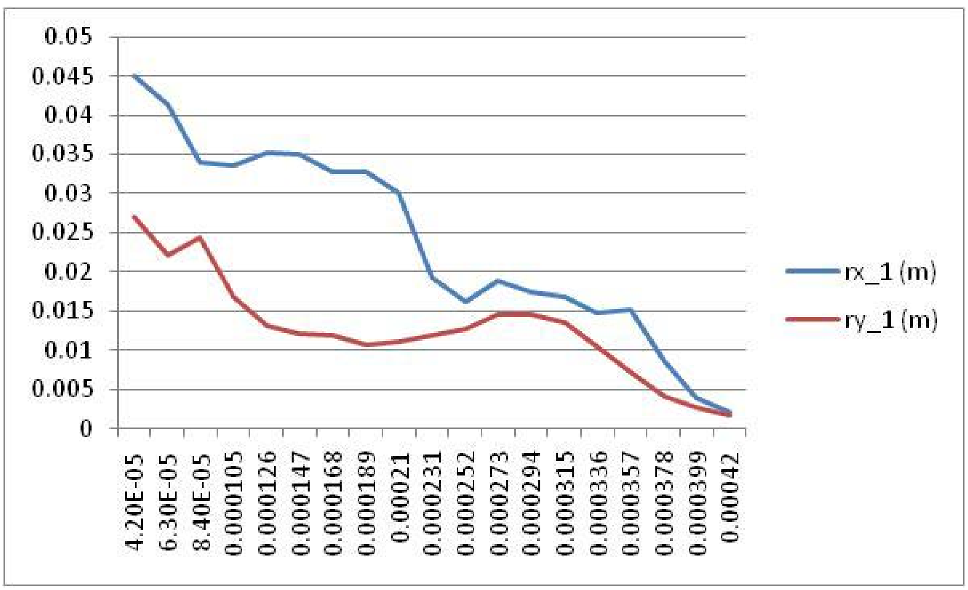

Figure 7. Shot 32 Radii vs. Time

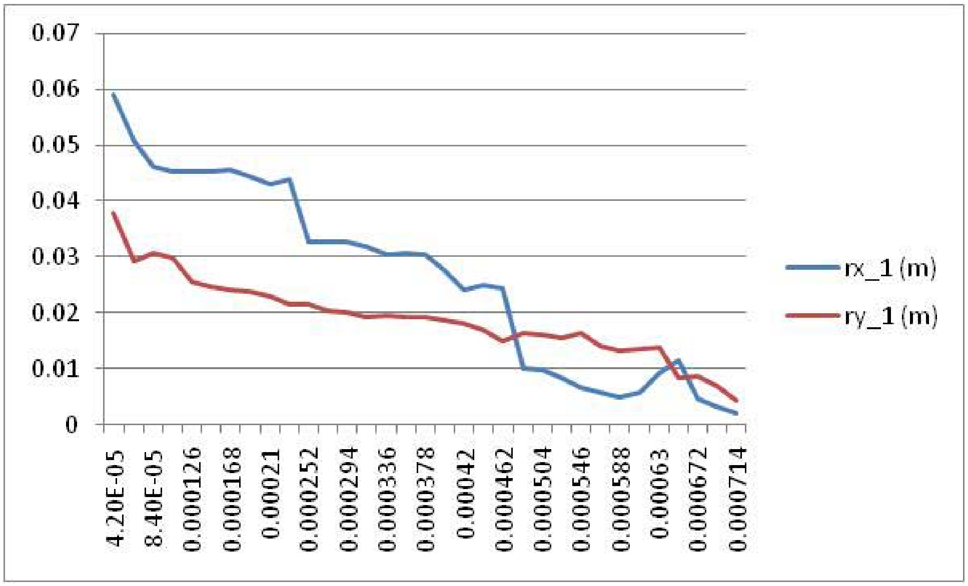

Figure 8. Shot 33 Radii vs. Time

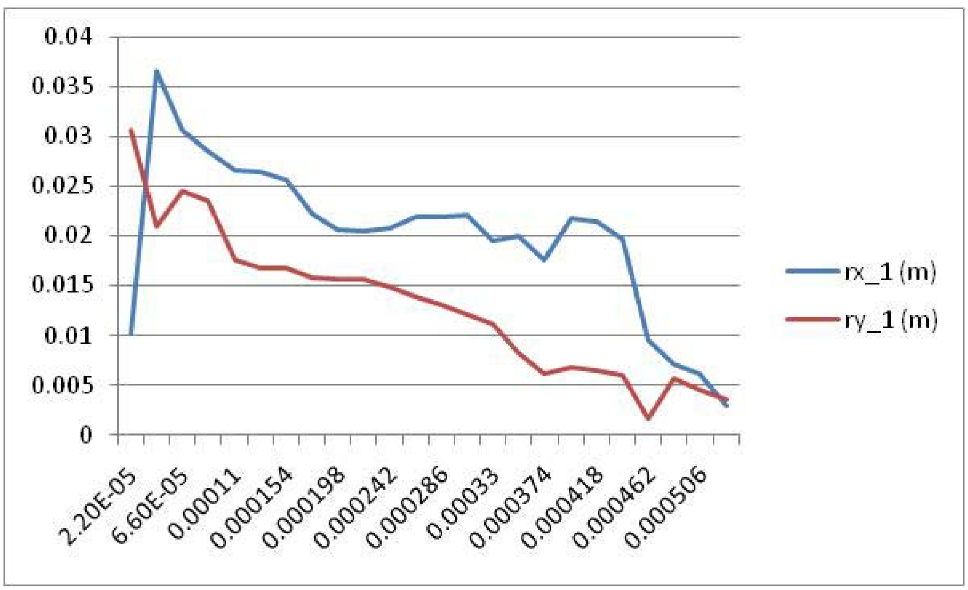

Figure 9. Shot 34 Radii vs. Time

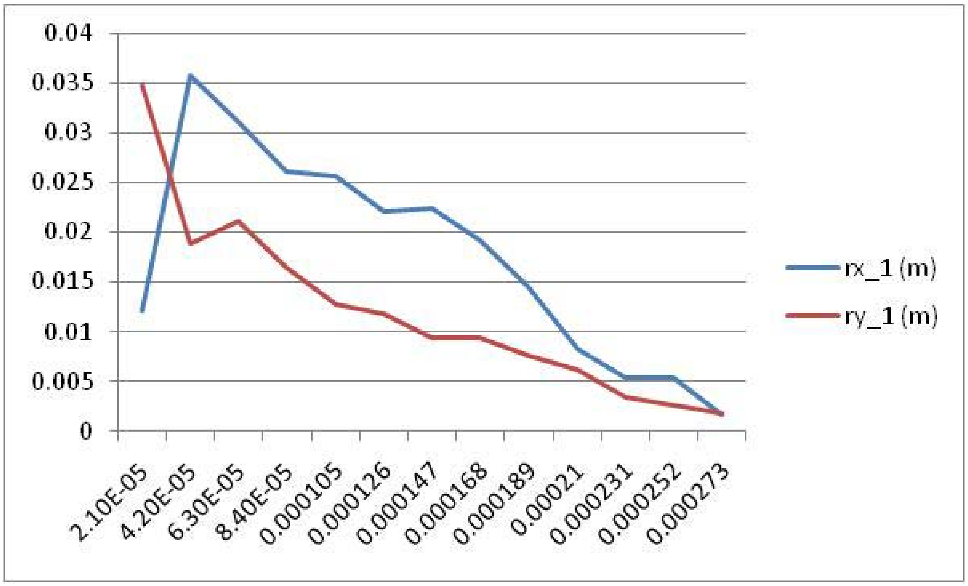

Figure 10. Shot 35 Radii vs. Time

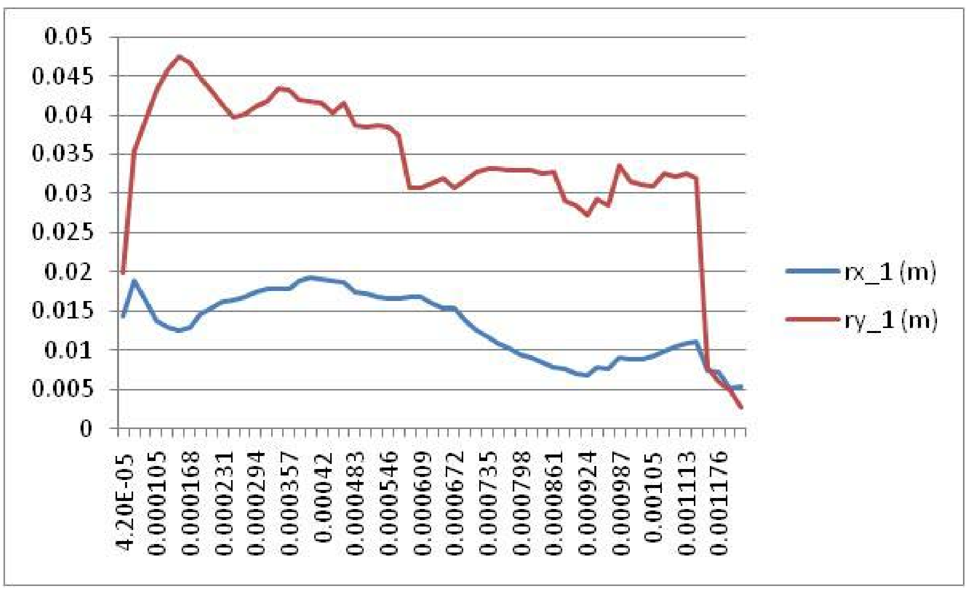

Figure 11. Shot 36 Radii vs. Time

Model Construction and Verification

Upon first examination of the response curves it appeared that a cubic regression model would fit best. This model would be of the form:

Flash radius was measured in meters, the β's are the model coefficients, and t represents time. JMP software was used to fit a separate model for both x-radius and y-radius data. A cubic model fit to the flash presented in Figure 3 is shown in Figure 12.

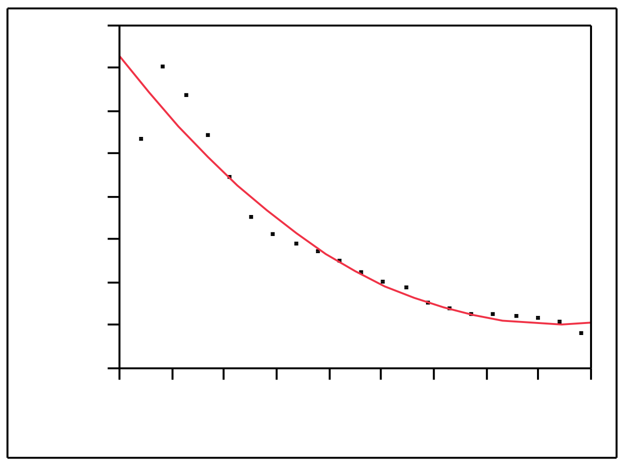

Figure 12. Cubic Model (red line) Fit of Flash Radius

While the model coefficients were found to be significant, and the fit was fairly good, problems were noted with the cubic model. First, at time zero the projectile has not yet impacted the surface, there is no flash and therefore no flash radius. So it was concluded that the model should start at the origin (the y-intercept in the model should be zero). Secondly, many of the flashes either build quickly and then plateau or have two peaks. The cubic model did not fit well for these flashes, and an example is shown in Figure 13. Cubic Fit of Flash with "Plateau".

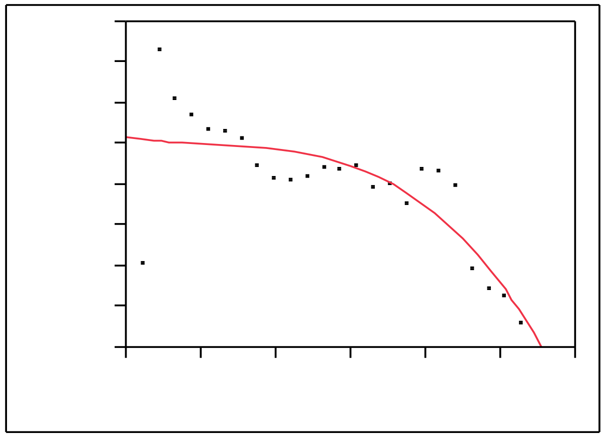

Figure 13. Cubic Fit of Flash with “Plateau”

It was determined that a quartic model could handle the plateau and two-peak flashes. The y-intercept was fixed at zero, and significant models were produced using JMP. The plateau flash from Figure 13 is shown again along with the quartic model in Figure 14.

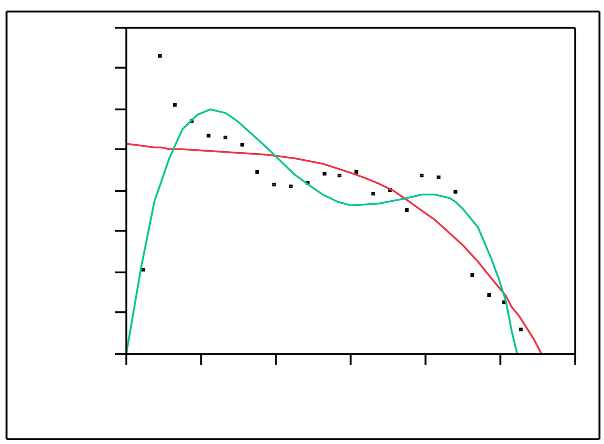

Figure 14. Cubic (red) and Quartic (blue) Fit of Flash with “Plateau”

Quartic models were produced for all eight test shots being considered. These models have the form:

Model Validation Methods

The eight test shots used were selected because they provided replicated points and design settings very similar in some cases. Model validation in the current context addresses:

- How well does the model capture the actual data?;
- How well does the model for one replicate model the other replicate?;
- How well does a model based on the aggregate data (both replicates) model the individual replicate?; and
- How well do aggregate data generate model with predictive capability across a variety of design points?

IV. Results

Individual Models

With eight test shots in the study, and flash radius data divided into x and y axes, there were 16 flash radius models derived. Each of the 16 equations had five coefficients (the β's), for a total of 80 coefficients in all. When checked for significance at the 95% level, 78 out of 80 coefficients were significant. The model plot for shot 11 is presented in Figure 15. The model equation for flash radius (x-axis) for this shot is:

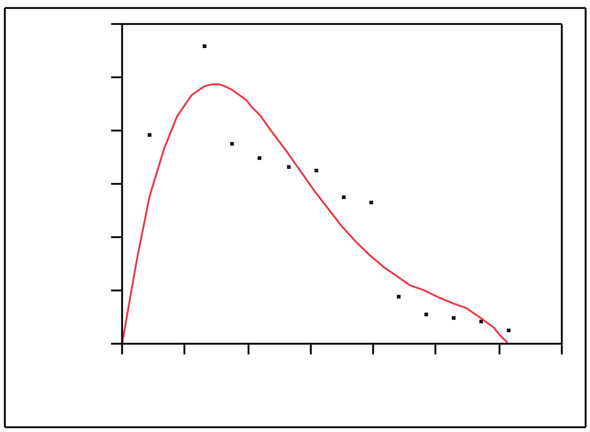

Figure 15. Shot 11, X-Radius vs. Time

Next, the residuals were examined to ensure that all assumptions for the regression analysis were met. First, they were checked to ensure constant variance and mean of zero. This was accomplished by examining a plot of residuals versus predicted values. This plot for shot 11 is presented in Figure 16.

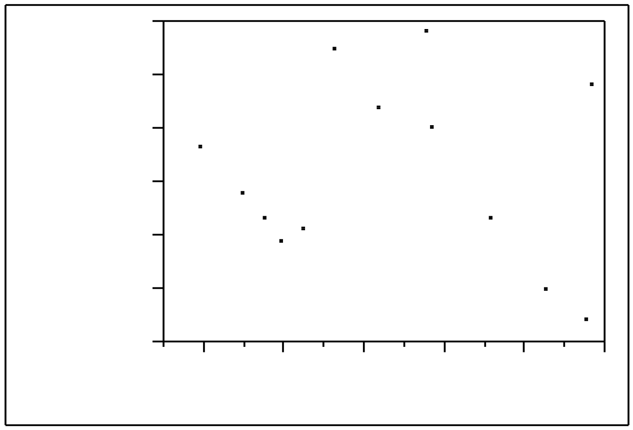

Figure 16. Residuals vs. Predicted (X-Radius) Values for Shot 11

The plots showed that the variance was fairly constant and that their mean was approximately zero for 6 out of 16 of the models.

Next the residuals were checked to ensure they were distributed normally. This was accomplished by producing a normal probability plot. Exactly half of the models' residuals were normally distributed according to the Shapiro-Wilkes Test. This meant that the assumptions required for the ANOVA to be valid were not met.

Taking each of the eight shot data individually produced significant models, however the assumptions required for the ANOVA to be valid were not met in every case.

Combined Replicate Models

The replicates were next combined and models produced. These models were then compared to the data from each of the original shots. The combined model for the x-radius for shots 11 and 12 is shown in Figure 17. The data points on the top are from shot 11, the ones on the bottom are shot 12. The model fit is the solid red line.

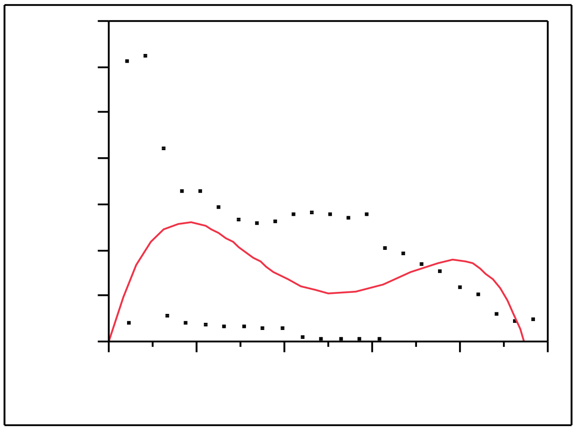

Figure 17. Combined Model: Shots 11 & 12, X-Radius vs. Time

While shots 11 and 12 were replicates with the same design settings, it is obvious that the shots produced very different results. Therefore this model has an averaging effect between the two sets of data. Similar results were obtained for the other three combined replicate data sets.

The residuals showed that variance was not constant, and that their distribution was normal for only three out of the eight models.

Additionally, when the residuals were plotted against time it showed that the residuals were time-dependent. These plots for the X and Y radii of the combined replicate model for shots 11 and 12 are presented in Figure 18 and Figure 19.

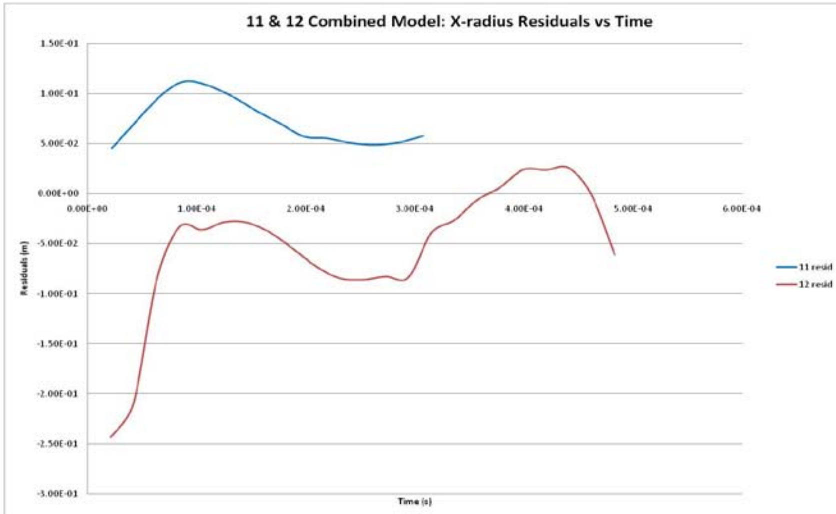

Figure 18. Combined Model: Shots 11 & 12, X-Radius Residuals vs. Time

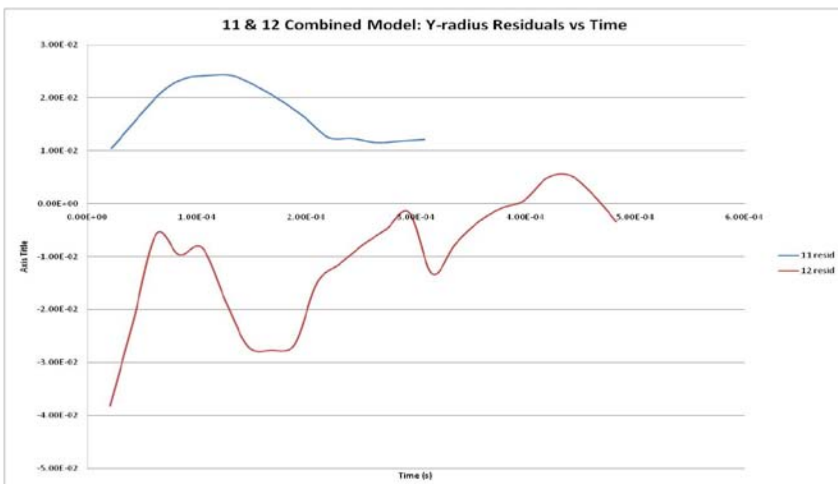

Figure 19. Combined Model: Shots 11 & 12, Y-Radius Residuals vs. Time

Appendix B includes the results for the other combined replicate models.

Multiple Combined Model

Finally, the data for shots 33, 34, 35, and 36 was combined to form one model each for x and y flash radius. As shown in Table 1, these sets of replicates differ only in projectile weight. Shots 33 and 34 used a 40 grain projectile, while shots 35 and 36 used a 75 grain projectile. This data was combined in order to see if projectile weight affected the flash radius. The models for the x and y radii are shown in Figure 20 and Figure 21.

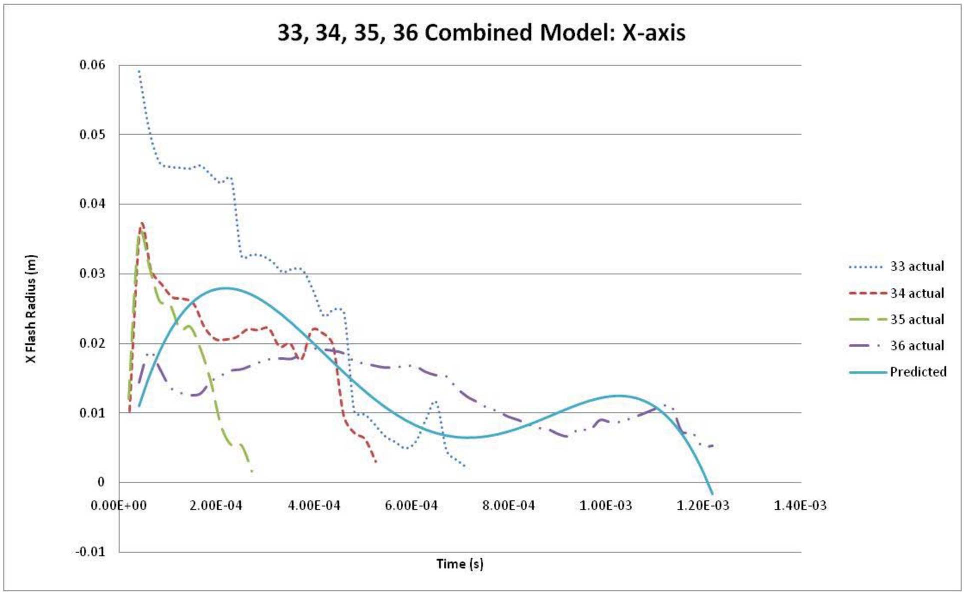

Figure 20. Combined Model: Shots 33, 34, 35, & 36, X-Radius vs. Time

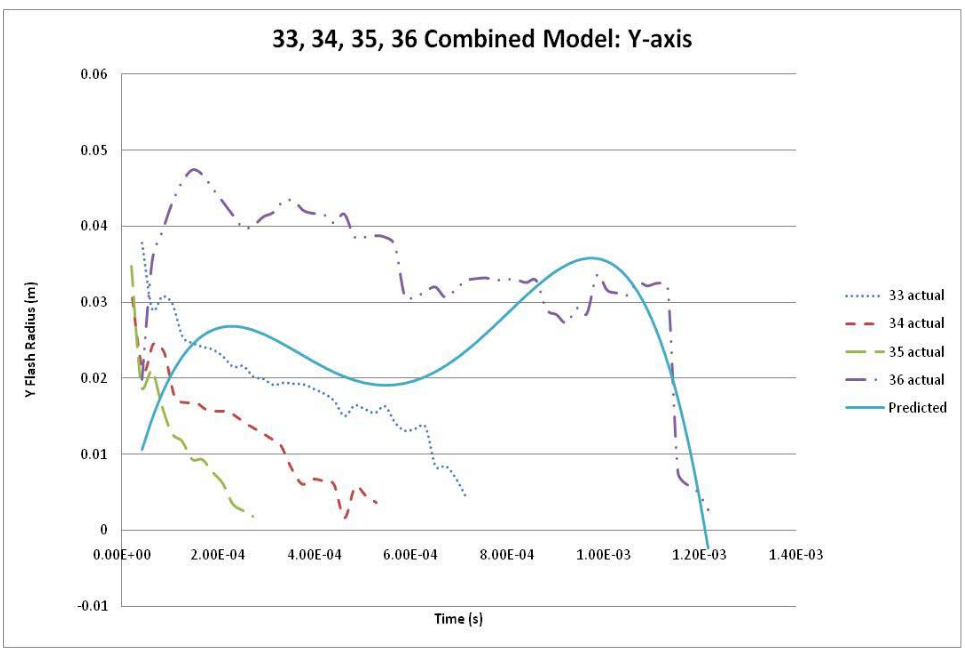

Figure 21. Combined Model: Shots 33, 34, 35, & 36, Y-Radius vs. Time

This combination produced significant models, and all coefficients were significant at the 95% level as well. Once again, however, the residuals were not normally distributed and the variance was not constant.

Discussion

The original idea for the final model of the flash radii was

$$Flash\ Radius = f(time) + N(0,\sigma^2)$$

Where f(time) is the regression-based model and $N(0,\sigma^2)$ is the error drawn from the normal distribution. However, since the residuals indicated non-constant variance and were not normally distributed, the error would have to be modeled separately. Therefore the final model for flash radius will likely be

$$Flash\ Radius = f(time) + g(time)$$

Where *g(time)* represents the error and is a time-series model.

V. Discussion and Conclusion

The individual quartic models for the test shots work very well to predict the flash radii. However, when combining the replicate data, the models predict roughly an average between the two radii. The fact that the same design settings produce very different flash radii causes this to happen. This difference adds to the already large amount of error.

More replicates are needed to fully account for the error in the combined models. Additionally, the assumption that the actual settings are equal to the design settings may need to be reconsidered. Actual shot velocity varied the most from its design setting. Another source of variability is the cube shape of the projectile in the test shots. It is theorized that different impact orientations of the cubes have an effect on the flash.

A future test consideration is to vary the impact atmospheric conditions, so that the effect of altitude on flash characterization could be examined.

Future work at AFIT on this effort will include refinement and improvement on the current modeling approach, as well as modeling the error component of the flash as a time-dependent function. Other possible future efforts would include modeling flash position, flash orientation, and exit side flashes. The models for residual mass and velocity from the 1990s could also be reexamined using the current high fidelity data.

Appendix A. Blue Dart

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word count: 222

Aircraft survivability analyses focus on the ability of an aircraft to emerge from hostile environments. Aircraft vulnerability assesses damage to the aircraft given hits by missiles, gun rounds, missile fragments, or other components of the threat environment. Analytical models of fragment impact need to address fragment penetration potential, incendiary flash characteristics on both entry and exit sides of the aircraft panels, and incendiary potential of the impact and subsequent flashes. Unfortunately, current modeling approaches are limited in both flash characterization and incendiary function estimation. In fact, no current models provide for incendiary flash characteristics. This research examines potential approaches to modeling flash characterization based on live-fire data.

This research used actual live-fire test data based on high-speed video analyses of fragment impacts against aircraft skin materials. Fragments of varied sizes were shot at various velocities. The high-speed video analyses yielded data on flash size, orientation and duration of the flash as well as post-impact, residual fragment velocity and residual fragment mass. Time-based models of flash width and length were developed and initial model validation was conducted. These preliminary results provide a viable approach for creating an empirical-based model of flash size that will ultimately be used for vulnerability assessments of aircraft versus missile attack. This research supports the Joint Survivability Working Group and the Aerospace Survivability Flight of the 46th Test Group.

Appendix B. Combined Replicate Models

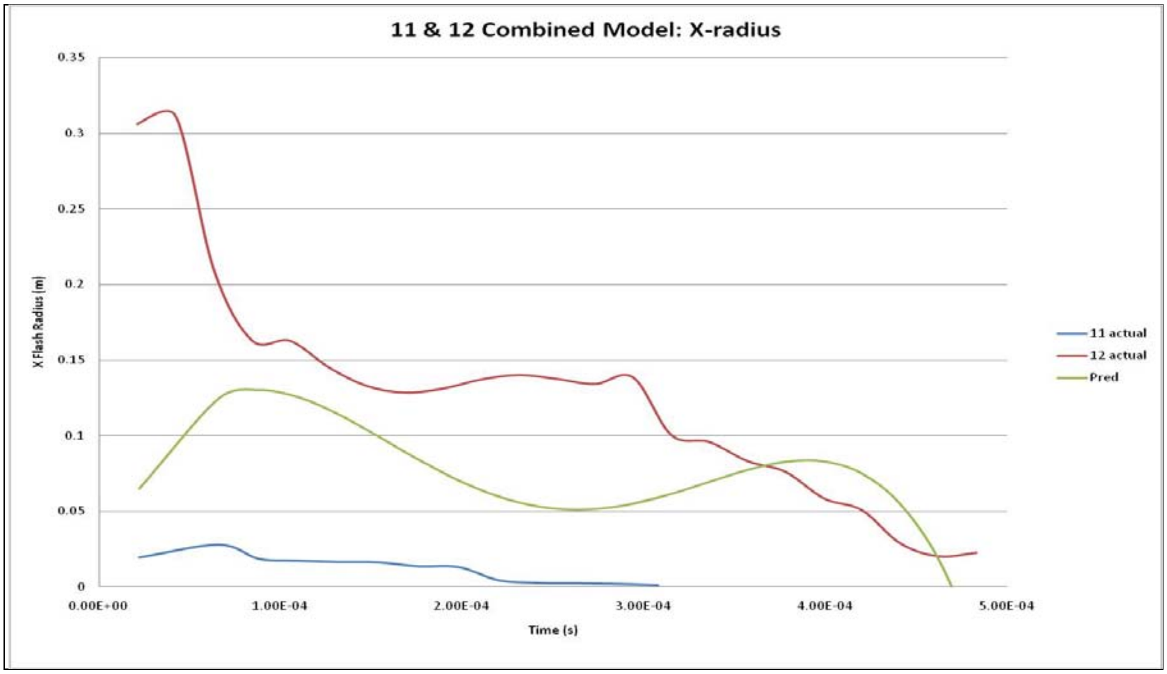

Figure 22. Combined Model: Shots 11 & 12, X-Radius vs. Time

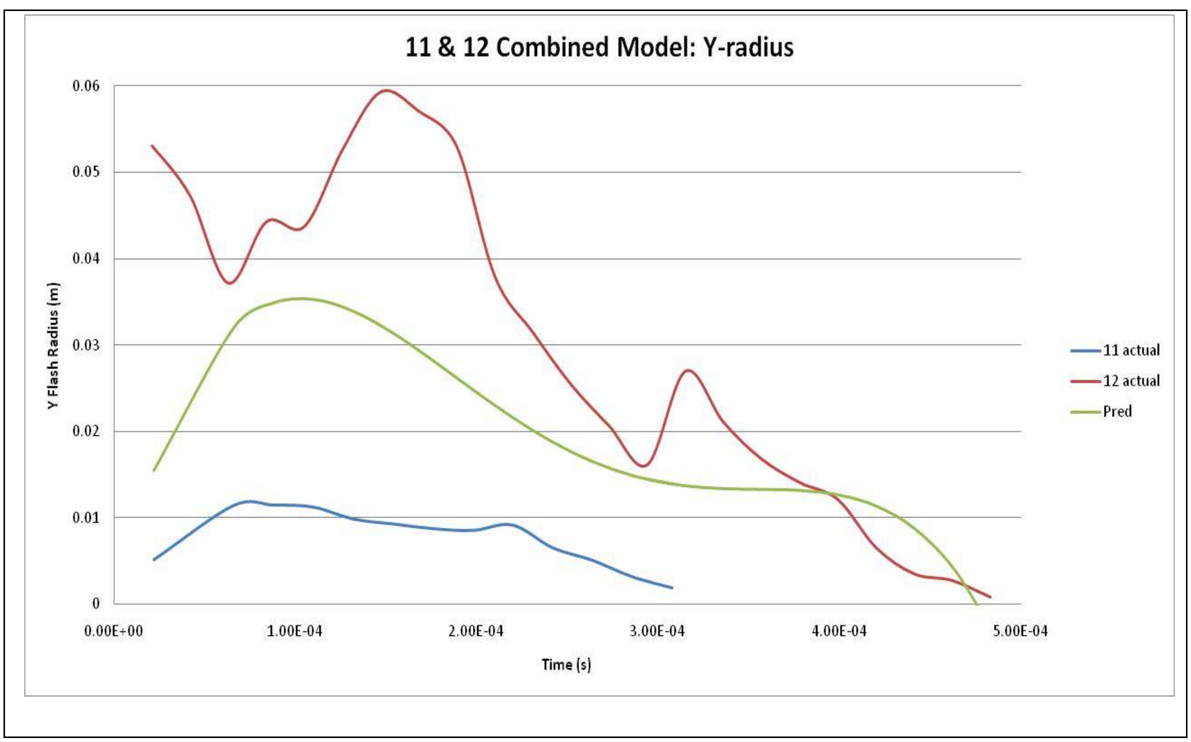

Figure 23. Combined Model: Shots 11 & 12, Y-Radius vs. Time

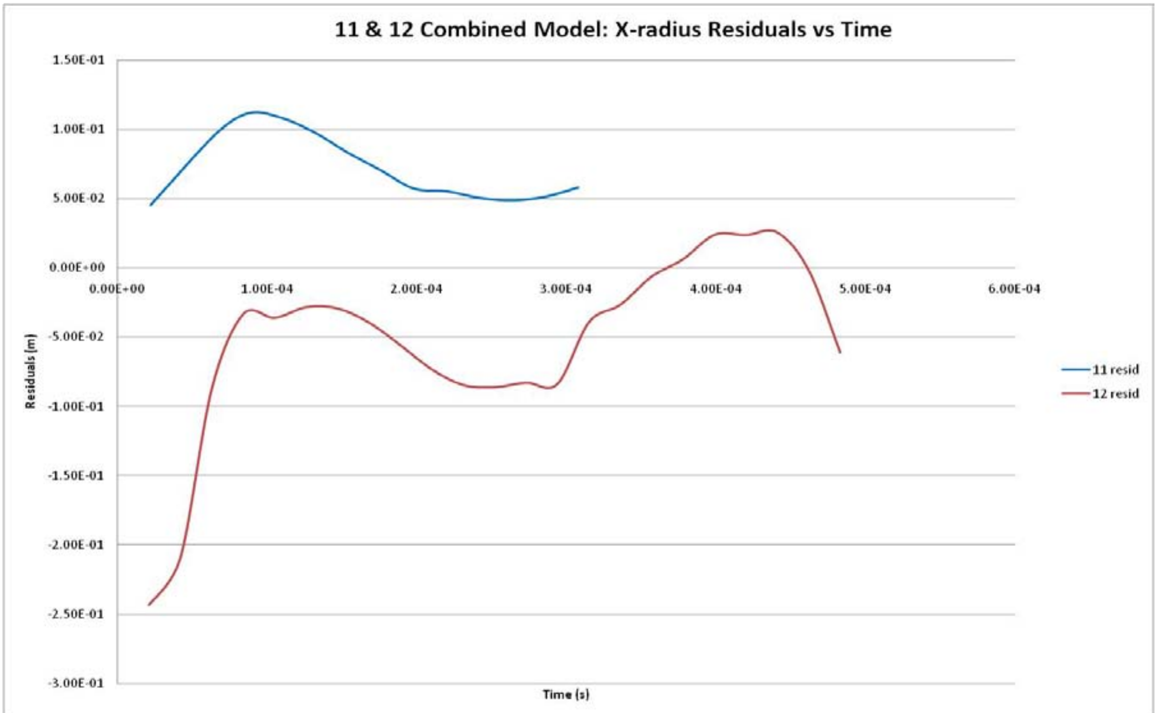

Figure 24. Combined Model: Shots 11 & 12, X-Radius Residuals vs. Time

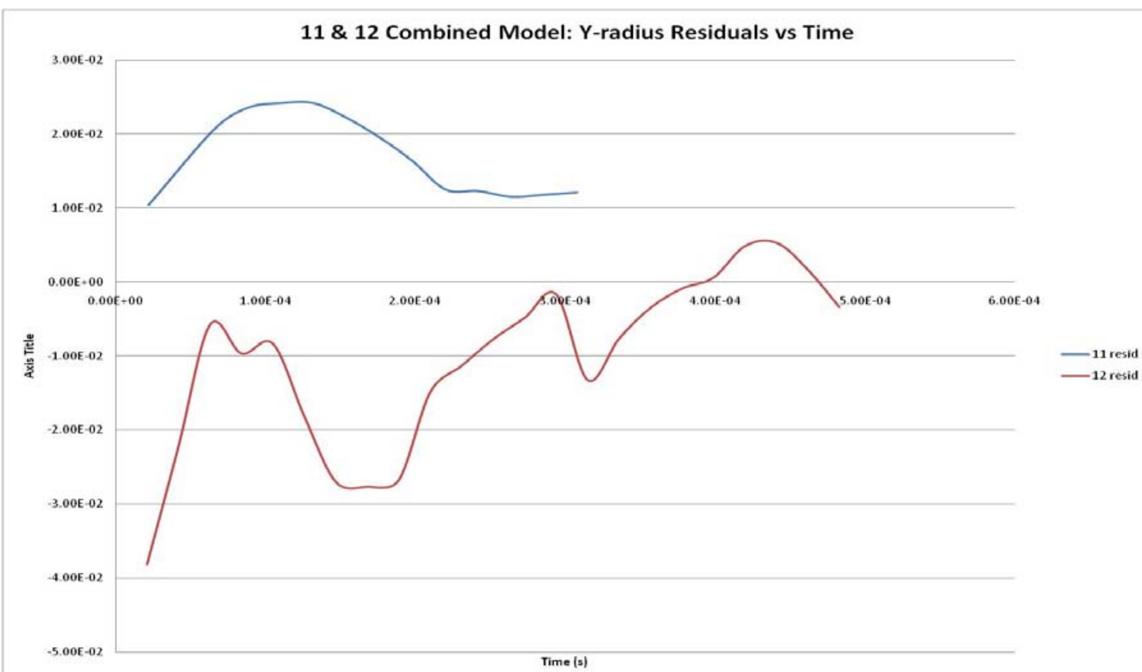

Figure 25. Combined Model: Shots 11 & 12, Y-Radius Residuals vs. Time

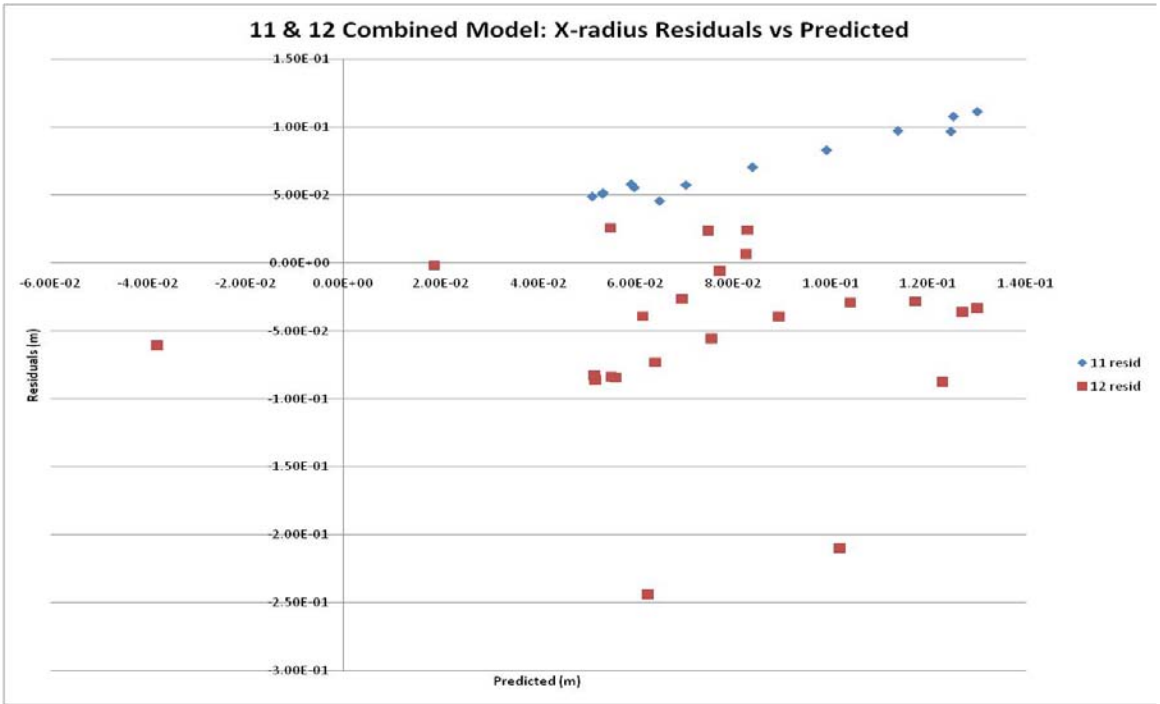

Figure 26. Combined Model: Shots 11 & 12, X-Radius Residuals vs. Predicted

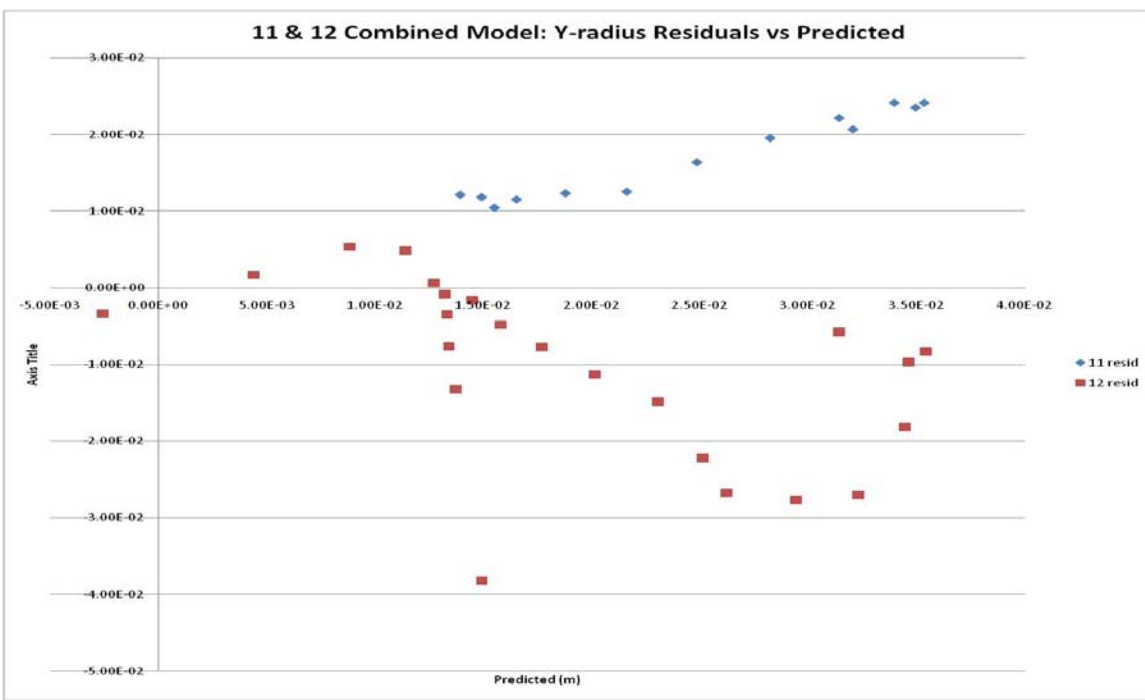

Figure 27. Combined Model: Shots 11 & 12, Y-Radius Residuals vs. Predicted

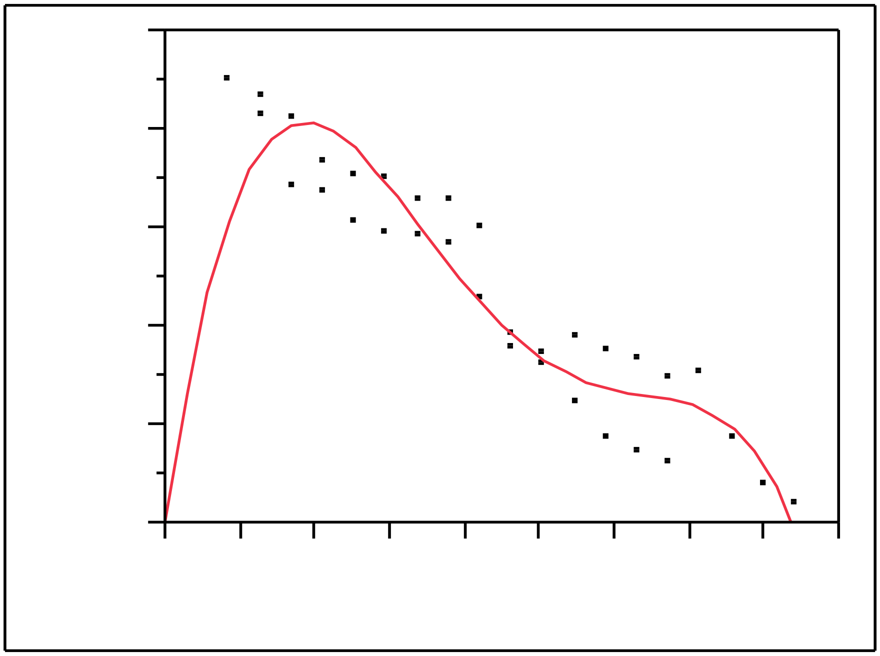

Figure 28. Combined Model: Shots 31 & 32, X-Radius vs. Time

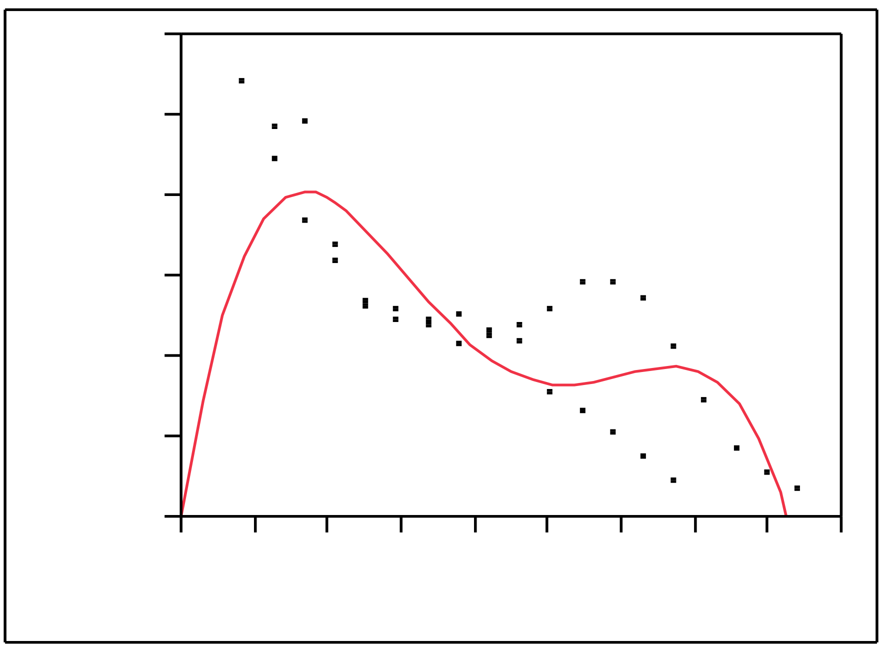

Figure 29. Combined Model: Shots 31 & 32, Y-Radius vs. Time

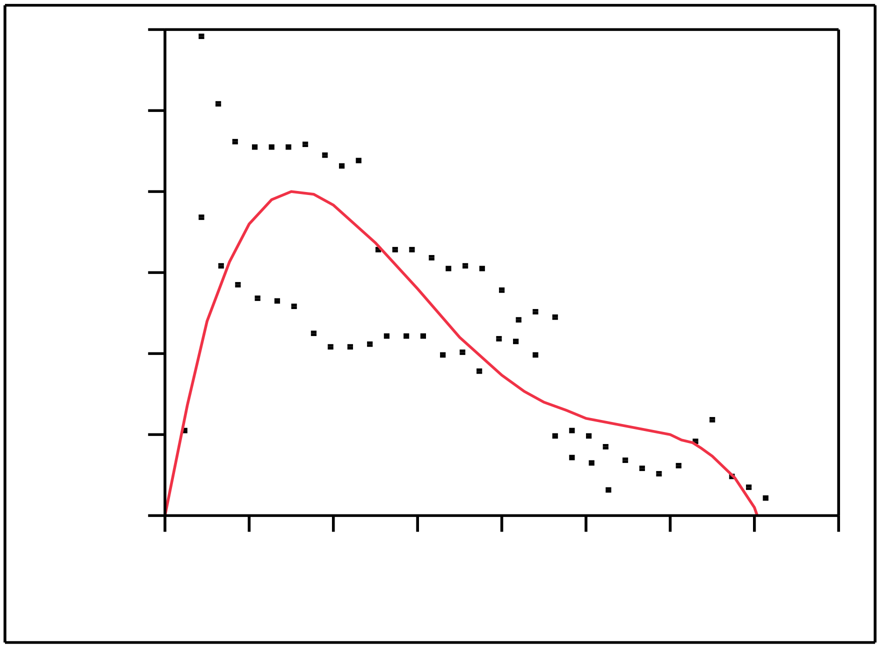

Figure 30. Combined Model: Shots 33 & 34, X-Radius vs. Time

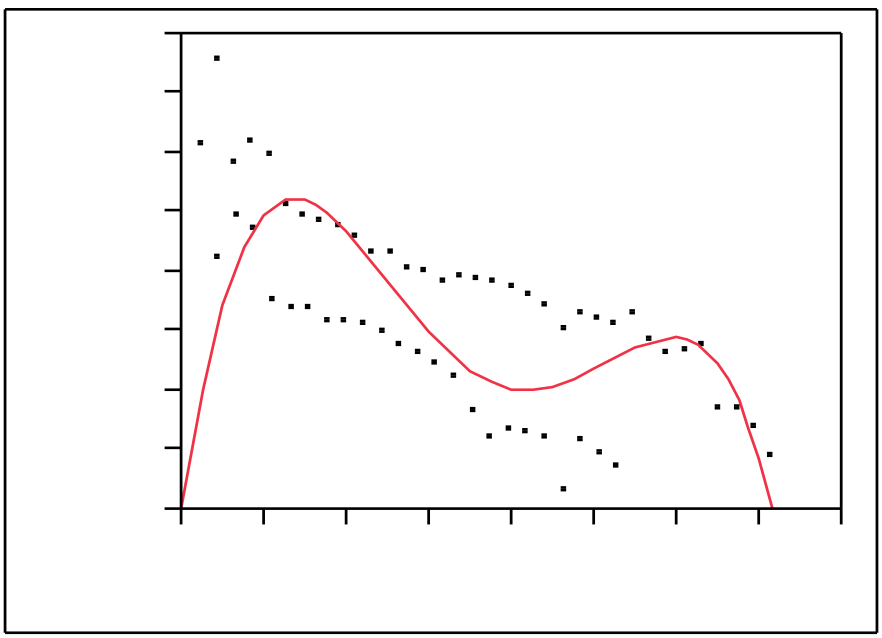

Figure 31. Combined Model: Shots 33 & 34, Y-Radius vs. Time

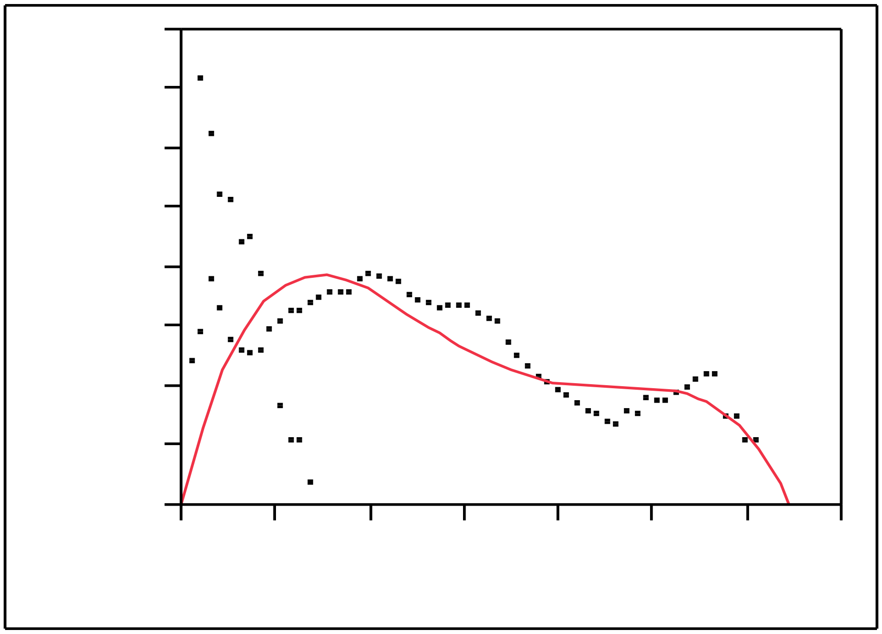

Figure 32. Combined Model: Shots 35 & 36, X-Radius vs. Time

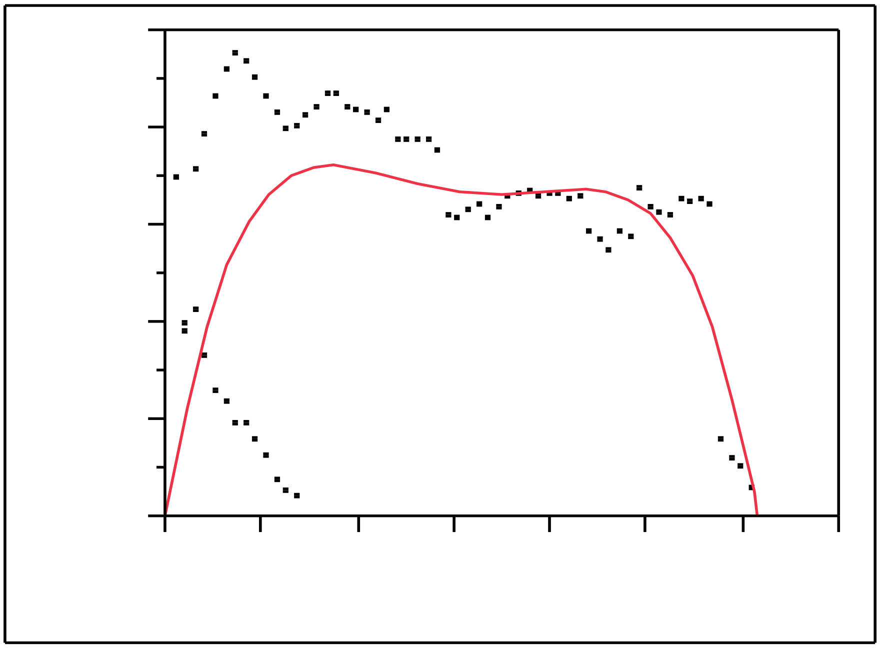

Figure 33. Combined Model: Shots 35 & 36, Y-Radius vs. Time

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14. ABSTRACT

Ballistic impact flash plays a pivotal role in the ignition of fires in military vehicles. Flash duration, geometry, and energy profiles are critical variables in the assessment of ballistic-induced fires. The survivability community has identified a need for a standardized data collection methodology and corresponding valid community verified models. This effort will quantify existing test data and begin the process of producing dynamic models for flash geometry based on projectile and target material properties and impact conditions.

15. SUBJECT TERMS

Regression; Ballistic Impact Flash; Projectile; Predictive Model; Aircraft Survivability; Incendiary Function

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