NATO STANDARD

AOP-65

FIRING TECHNIQUES TO DETERMINE BALLISTIC DATA FOR FIRE CONTROL SYSTEMS

Edition A Version 1
AUGUST 2018

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION (NATO)

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NATO LETTER OF PROMULGATION

22 August 2018

1. The enclosed Allied Ordnance Publication AOP-65, Edition A, Version 1, FIRING TECHNIQUES TO DETERMINE BALLISTIC DATA FOR FIRE CONTROL SYSTEMS, which has been approved by the nations in the NATO ARMY ARMAMENTS GROUP is promulgated herewith. The agreement of nations to use this publication is recorded in STANAG 4144.

2. AOP-65, Edition A, Version 1, is effective upon receipt.

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4. This publication shall be handled in accordance with C-M(2002)60.

Zoltán GULYÁS
Brigadier General, HUNAF
Director, NATO Standardization Office

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RECORD OF RESERVATIONS

CHAPTER	RECORD OF RESERVATION BY NATIONS
Note: The reservations listed on this page include only those that were recorded at time of promulgation and may not be complete. Refer to the NATO Standardization Document Database for the complete list of existing reservations.	

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RECORD OF SPECIFIC RESERVATIONS

[nation]	[detail of reservation]
ALB	Albanian Armed Forces will use as a standard artillery weapons systems and fire control systems from the nations that we will purchase our artillery equipment.
CZE	CZE Armed Forces do not use cluster munitions according to the Act No. 213/2011 Coll., in valid statues at large.
LVA	LVA NAF intend to use STANAG 4144 in case of necessity to define FCI data for existing or newly purchased ammunition.
TUR	As of DOP, only the parts of STANAG those are related to indirect fire are implemented.
USA	Releasability is too broad because it includes PFP. Delete PFP and add Partnership: Interoperability Platform (PIP) initiative. The selection of IP partners based on participation in exercises, operations, the NATO Response Force, the Partnership for Peace Planning and Review Process and the Operational Capabilities Concept and the annual review of those partnerships establishes a selective and conscious decision to include selected member nations and exclude selected PFP member nations from releasablility as appropriate.
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1 AIM

The principal aim of this agreement is to standardize procedures to determine and exchange the Fire Control Inputs for NATO Surface to Surface indirect and direct fire systems. Fire Control Inputs contain the set of fixed technical data for the gun-ammunition combination which are used by Fire Control Computers implementing NATO standard trajectory models (such as in STANAG 4355) and to create manual gunnery solutions, e.g., tabular firing tables.

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2 AGREEMENT

Participating countries agree to use these procedures for determining the Fire Control Inputs for Surface to Surface (and certain Surface to Air) systems using the NATO Modified Point Mass model as defined in STANAG 4355. Participating countries that wish to exchange Fire Control Inputs also agree to provide the supporting Test Data Summary.

This agreement is currently not applicable to the following systems:

a) Rockets
b) Guided ammunition

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3 DEFINITIONS

The definitions used in this STANAG are given in Annex A.

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4 GENERAL

This document specifies the NATO procedures to be used for the creation of Fire Control Inputs for use in Fire Control Systems implementing NATO standard trajectory models. This will facilitate the exchange of Fire Control Inputs between NATO countries without substantial additional firings. The data to be determined concerns all parameters as defined in STANAG 4355 and all additional parameters required for the preparation of fire control systems including data for pyrotechnic munitions, submunition trajectories, rocket assisted trajectories, base burn trajectories, and tracer trajectories.

STANAG 4106 applies to indirect fire systems when the test weapon/munition configuration is expected to be ballistically matched or similar to existing validated Fire Control Inputs. In all other cases the ballistic performance of the new configuration must be determined following the procedures in this STANAG.

For Fire Control solutions based on a Point Mass Trajectory Model (e.g. most direct fire and mortar systems) only those procedures applicable to that model should be selected.

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5 DETAILS OF THE AGREEMENT

5.1 Introduction

The creation of Fire Control Inputs requires analysis of data gathered from dynamic firing tests and other measurements, computer simulations and, if possible, from previously determined Fire Control Inputs. The test design for the firing tests depends on the type of projectile, the available instrumentation and the required data to be determined and/or validated. An Aerodynamic Firing Test, demanding advanced in-flight instrumentation, should be used to determine aerodynamic coefficients and ballistic performance from firing test results. If the aerodynamic coefficients are drafted by non-firing test techniques then a Ballistic Performance Firing Test may be used that allows a limitation in instrumentation (possibly to a minimum level of fall of shot measurements). Details on firing test designs are to be found in Annex B and on firing test data analysis in Annex C.

5.2 Multi-Charge Weapon Systems

For Multi-Charge weapon systems, Fire Control Inputs must be determined for all charges.

5.3 Multi-Trajectory Phase Projectiles

For Multi-Trajectory Phase Projectiles (e.g. Carrier Projectiles and/or Assisted Projectiles) Fire Control Inputs must be determined for all trajectory phases. At least the start of end position and time of flight are to be determined for each trajectory phase of the carrier and/or pay.oad(s). IN-flight data for several phases may e measured successively but are to be analyzed in the following order:

a) Data related to the unassisted carrier trajectory;

b) Data related to the assisted carrier trajectory;

c) Data related to submunition(s) trajectories;

5.4 NATO Modified Point Mass and Five Degrees of Freedom Models

The NATO Modified Point Mass and Five Degrees of Freedom Models as defined in STANAG 4355 do cover rockets and guided artillery ammunition. However, new test requirements for these systems are not addressed in this edition of AOP-65, but will be addressed in a future edition.

5.5 Categories of Data for Fire Control Inputs

a) Physical data

b) Internal ballistic data

c) External ballistic data

  i) Aerodynamic coefficients

  ii) Fitting factors and correction factors

  iii) Probable errors

d) Auxillary data (optional)

5.6 Meteorological Conditions

Meteorological conditions will vary at any given range and firing date. In order to remove the effect of these conditions on the aerodynamic coefficients and fitting factors, it is required to take meteorological data, both at the surface and aloft to at least 300 m above maximum ordinate for indirect fire systems or to at least 10 meters above the maximum ordinate for direct fire systems. Preferably these meteorological data should not be stale in time and space. Data gathering should begin before the first round is fired and end after the last round is fired. Details on the meteorological requirements are defined in Annex D.

5.7 Physical and Motor Data

Physical and motor data are to be determined by national procedures. All physical data and most motor data can be determined prior to the firing tests, some motor data are also determined suing firings. Preferably, the statistical spread for each parameter is determined for use in the error budget as defined in Annex I. The sample size and number of manufacturing lots should be representative of the national munition inventory. It must be specified whether the spread means a standard deviation, probable error, confidence interval or otherwise. A list of physical data and motor data is given in Annex E.

5.8 Internal Ballistic Data

Internal ballistic data procedures are described in Annex F.

5.9 Aerodynamic Coefficients

Aerodynamic coefficients are functions of Mach number. A list of aerodynamic coefficients specified for different types of projectiles is given in Annex G. The method to establish aerodynamic coefficients is specified in Annex B. It depends on instrumentation and analyses made.

a) In case of ballistic match or similitude with an existing projectile, aerodynamic data of the existing projectile can be used. The determination of ballistic match or ballistic similitude for indirect fire ammunition is described in STANAG 4106.

b) Usually the aerodynamic coefficients for a projectile/fuze combination are determined for one gun/charge system. These coefficients are applicable for all possible gun/charge systems within the same Mach range. If the differences in gun or in charge system can be taken into account by modifying only the fitting factors then STANAG 4106 should be applied.

5.10 Fitting Factors

Fitting factors are used to take into account all physical phenomena, which are not included in the equations of motion. The fitting factors should minimize the mean bias between predicted and observed mean points of impact at a certain occasion for rounds fired in apparently the same firing conditions and aiming elements (e.g. quadrant elevation, azimuth and fuze setting). Thus calibrating the equation of motion to represent the mean ballistic performance, which is expected when firing over a large number of firing conditions and occasions. The fitting factors are listed in Annex H. The method to establish fitting factors is described in Annexes B and C.

5.11 Round-to-Round Probable Errors

Round to round probable errors represent the round-to-round variation around the mean point of impact (or air burst). These errors are derived from firing a series of rounds from a single gun within a single occasion, where each round is fired under apparently the same firing conditions and aiming elements (e.g., quadrant elevation, azimuth and fuze setting). The dispersion is due to random variations in meteorological and ballistic firing conditions and random changes in aiming elements and other unaccountable factors. The probable errors are a function of the weapon-projectile-charge combination and the quadrant elevation. There are two ways to calculate the numerical values of the probable errors for range, deflection, time to burst, range to burst and height of burst. Both ways, given in Annex I, take into account the results of live firings. The method to establish probable errors is described in Annexes B and C.

5.12 Auxiliary Data

Auxiliary data contain optional parameters supporting numerical iterations and values for safety and interchangeability validations for the Fire Control System. The determination of these parameters is never part of firing test designs. Safety parameters must be determined prior to the firing tests. Numerical parameters are computed after validation of the interior and exterior ballistic data (e.g. system parameters for quadrant elevation iteration and closed form approximation equations used to speed numerical processing).

5.13 The instrumentation and measurements to be applied

The instrumentation and measurements to be applied depend on the test design as defined in Annex B. The Fall of Shot method given in STANAG 4106 should not be used for other than ground impact unassisted projectiles for ranges below 20 km. If available a Doppler or Tracking Radar System should be used. The instrumentation and measurements for range firing tests are identified in Annex B.

5.14 Test Data Analysis

The method of analyzing the firing data is dependent on the test designs describe in Annex B. The methods for data analysis for both the ballistic performance and aerodynamic firing test design are described in Annex C.

5.15 Exchange of fire control inputs

Fire Control Inputs for Surface-to-Surface indirect and direct fire systems to be exchanged from on NATO country to another will be available in the format and files defined in AOP-37, Database Design Specification, for use in the NATO Armaments Ballistic Kernel. A Test Data Summary as defined in Annex J is required to complete the process.

6 IMPLEMENTATION OF THE AGREEMENT

Ratification and implementation of this STANAG will ensure that Fire Control Inputs for indirect and direct fire systems developed by one NATO country for a common weapon system can be effectively used by any other NATO country without substantial additional firings. It will also ensure that Fire Control Inputs developed for one nation’s gun/propelling charge system(s) can be reliably converted to another nation’s different gun/propelling charge system(s) with minimal additional firings.

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ANNEX A DEFINITIONS

Aerodynamic coefficient	The parameters defined as a function of Mach number to quantify the forces and moments acting on a body in flight.
Base burn (BB)	A method of generating gas to fill the partial vacuum at the base of the projectile during flight, in order to reduce drag and so extend the range of the projectile (also Base Bleed).
Ballistic coefficient (C)	The range fitting factor used to calibrate trajectory models. Artillery systems typically use the form factor (see below).
Ballistic match	When there is no significant difference between the points of impact and the probable errors of two interchanged ammunitions, for every charge and elevation, then they are ballistically matched.
Ballistic performance	The average flight behavior of mortar or artillery shells.
Ballistic similitude	When two interchanged ammunitions, with or without application of the ballistic corrections, fall within defined limits for every charge and elevation then they are ballistically similar. The limits are defined by three levels, i.e. one probable error, one percent in range and five percent in range.
Bourrelet nubs	The canted protrusions on the ogive of a projectile that center the projectile in the bore.
Cartridge	Ammunition, ready for firing, wherein the propelling charge(s), its primer, with or without the projectile with its fuze are assembled in one unit for handling and firing. (AOP-38)
Correction factor	The physical parameter or function used to adjust a standard FCI parameter for non-standard conditions.
Charge	See Propellant.
Deflection	The angle between the vertical plane through the line of departure and the line from weapon to point of impact due to drift , Coriolis and wind effects.
Direct fire	Fire delivered on a target that is visible to the aiming unit; includes tank and small arms fire. (AAP-6) Fire directed at a target which is visible to the aimer.
Drag factor (f_d)	The range fitting factor modifying the drag force, alternative to form factor.

Drag force (F_D)	The aerodynamic force opposing the forward velocity of the projectile.
Drift	A deflection component. The shift in projectile direction perpendicular to the azimuth of fire due to gyroscopic action which results from gravitational and atmospheric induced torques on the spinning projectile. (AAP-6) a shift in projectile direction due to gyroscopic action which results from gravitational and atmospheric induced torques on the spinning projectile.
Droop	The bending of a gun barrel in the vertical plane; it is measured by the vertical angle between the bore axis at the commencement of rifling and the axis of the bore at the muzzle.
Error budget	Types and magnitudes of factors influencing the errors in the delivery of the projectile to its target.
Fall of shot method	A ballistic firing test to determine the fitting factors primarily using point of impact measurements.
Fire Control Inputs (FCI)	The set of fixed technical data for a gun-ammunition combination used by fire control computers implementing a NATO standard trajectory model.
Fitting factor	An empirically determined parameter used to minimize the mean bias between the theoretically predicted parameters and the ballistic performance.
Fork	The change in the angle of elevation necessary to produce a change in range at the level point equivalent to four probable errors in range.
Form factor (i)	The range fitting factor modifying the drag force. This is typically a function of charge and quadrant elevation.
Horizontal miss distance	The distance to the left or right from the aim point on a vertical target to a projectile impact.
Indirect fire	Fire delivered on a target that is not itself used as the point of aim for the weapon; includes artillery, mortars, and most naval fire. (AAP-6) Fire delivered at a target which cannot be seen by the aimer.
Jump	The component in the vertical plane containing the bore axis, of the angle at the muzzle between the direction of the bore axis before firing and the line of departure of the projectile.
Lift factor (f_l)	The fitting factor modifying the lift force, primarily affecting deflection. Typically it is a function of charge and quadrant elevation.

Lift force (F_L)	The aerodynamic force perpendicular to the trajectory, tending to pull the projectile in the direction its nose is pointed.
Mach number (M)	The ratio of the speed of the projectile and the local speed of sound.
Magnus force (F_{mag})	The aerodynamic force perpendicular to the plane of yaw (typically pointing up in the vertical plane for the spinning shell) and primarily affecting the time of flight and the maximum ordinate.
Magnus force factor (Q_M)	The fitting factor modifying magnus force. It primarily affects the time of flight. It is assigned a value of one in STANAG 4355.
Modified Point Mass Trajectory Model (MPM)	The NATO standard 4 degrees of freedom model for spin stabilized cannon and mortar projectiles; defined in STANAG 4355.
Muzzle velocity (MV)	The speed of the projectile when it leaves the barrel. In interior ballistics the speed can be estimated using an interior ballistic model. In exterior ballistics the speed is obtained by extrapolating down range measurements of projectile velocity to the muzzle position.
Point Mass Trajectory Model (PM)	The NATO standard 3 degrees of freedom mathematical model representing the flight of a projectile accomplished by simplifying the Modified Point Mass Trajectory Model; defined in STANAG 4355 Annex F.
Probable error (PE)	The interval at which an event is just as likely to happen as not. Typically in exterior ballistics, it is the 1-dimensional interval representing 50% of the points of impact or burst around a mean of impact or burst within a single average occasion.
Projectile	An object, projected by an applied exterior force and continuing in motion by virtue of its own inertia, as a bullet, shell or grenade. (AOP-38)
Propellant (Charge)	Substance or mixture of substances used for propelling projectiles and missiles. (AOP-38)
Round	All the parts that make up the ammunition necessary in firing one shot. (AOP-38)
Spin damping moment (M_{spin})	The aerodynamic moment characterizing the decrease in spin rate during flight.
Submunition	Any munition that, to perform its task, separates from a parent munition. (AAP-6)

Thrust factor (f_T)	The fitting factor used to match the observed motor performance for rocket assisted projectiles.
Throw-off	The component in the horizontal plane at the muzzle, of the angle at the muzzle between the direction of the bore axis before firing and the line of departure of the projectile.
Tracer	A small pyrotechnic charge in the base of a projectile which ignites upon firing making the projectile's trajectory visible to the naked eye. Pyrotechnic element or sealed article containing pyrotechnic substances designed to enable optical tracking of the trajectory of a projectile. (AOP-38)
Trajectory	The 3-dimensional curve described by the center of gravity of a projectile in flight.
Vertical miss distance	The distance above or below the aim point on a vertical target to a projectile impact
Vertical target method	A ballistic firing test to determine the fitting factors for direct fire primarily using point of impact measurements on an upright (vertical) target.
Yaw	The angle between the longitudinal axis of a projectile at any moment and the tangent to the trajectory. (AAP-6) Angle between the longitudinal axis of a projectile at any moment and the tangent to the trajectory in the corresponding point of flight of the projectile.
Yaw drag factor	The fitting factor modifying the quadratic yaw drag coefficient and primarily affecting range especially at high angles of fire.
Yaw of repose	The residual equilibrium yaw resulting when the axis of the gyroscopic stabilized projectile falls away from the trajectory as it curves downwards due to the gravity.

ANNEX B FIRING TEST DESIGNS

1) TEST DESIGN SELECTION

a) The determination of FCI by means of tests can be separated in the following different parts:

i)	Determination of physical and motor data	(Annex E)
ii)	Determination of aerodynamic data	(Annex G)
iii)	Determination of ballistic fitting factors	(Annex H)
iv)	Determination of probable errors	(Annex I)

Some of these parts may be combined. The firing test designs in this Annex cover the parts 3, 4 and 5. For these firing tests meteorological soundings are required to be made in accordance with Annex D.

b) Aerodynamic coefficients. Prior to the determination of ballistic data the aerodynamic coefficients should be drafted by national procedures and be substantiated simultaneously with the ballistic data. The method of determination depends on the available equipment. The required aerodynamic coefficients for all types of projectiles are a function of Mach number.

c) The following methods are in use:

- Wind tunnel
- Aeroballistic range: - Using standard spark photography techniques to extract the aerodynamic coefficients for small to medium yaw angles (< 15°)
- Software based: - Using full computational fluid dynamic codes (CFD) and or semi-empirical techniques based on interpolation among tabulated aerodynamic data for typical projectile designs and shapes.
- Full scale firings: - As described in the following designs, in combination with the Test data analysis in Annex C.

d) Similitude: In case of similitude with an existing indirect fire system STANAG 4106 should be applied.

e) In general, the test design and associated sample sizes are determined by the performance requirements of the ballistic fire control system and the known or estimated variability of the factors involved, i.e., the aerodynamic coefficients, fitting factors and probable errors. Both within test group (round-to-round) and between test groups (occasion-to-occasion) variability must be considered. The observed variabilities will be reported as described in Annex J.

f) There are several approved test designs for the determination of ballistic performance. These test designs are described in the rest of this annex. However, other test designs may be possible. These designs may be used subject to approval of the NAAG/ICG-IF/SG2. Approval must be reached through the national delegate in this subgroup.

2) BALLISTIC PERFORMANCE FIRING TEST DESIGNS

a) The following test designs may be used to determine ballistic performance (ballistic fitting factors and probable errors) for given aerodynamic coefficients. Firings from the aerodynamic firing test design (section 3) may also be applied for the ballistic performance.

b) Fall of Shot Method (Indirect Fire)

i) In order to determine an appropriate test design as well as the number of rounds required to estimate the fitting factors and the probable errors, the required performance of the ballistics must be specified. In this example, the following typical performance requirements are assumed:

- mean performance – the range versus quadrant elevation relationship must be within ± 0.5 % of range of the true value with 90% assurance.
- dispersion – the estimated probable errors must be within ± 30 % of the true dispersion.

Given the aerodynamic coefficients needed for the MPM or PM Model (see paragraph 1.c) and using estimates of the within group and between group variability of the ballistic factors:

(1) Artillery and Naval Indirect Gunfire Systems – The design shown in Table B.1 will meet the assumed requirements for artillery and naval gunfire systems.

Table B.1: Test Design Fall of Shot Method for Spin Stabilized Artillery

Approximate Quadrant Elevation (mils)	All Charges[a]
350	5,5
550	5,5
750	5,5*
950	5,5
1150	5,5*

Where 5,5 means fire 5 test rounds on each of 2 occasions. 5,5* means that in these series a yaw sonde should be used on as many projectiles as described in national procedures. The relevant warmer rounds are not included.

(a) Note that naval systems commonly use fixed cartridges and may only have one standard charge (muzzle velocity).

(2) Mortars – The design shown in Table B.2 will meet the assumed requirements for mortars.

Table B.2: Test Design Fall of Shot Method for Mortars

Approximate Quadrant Elevation* (mils)	All Charges
800	5,5
1050	5,5
1300	5,5
1500	5,5

Where 5,5 means fire 5 test rounds on each of 2 occasions. The relevant warmer rounds are not included.

*Note – the minimum, maximum, and intermediate quadrant elevations may need to be adjusted to account for weapon systems that incorporate a direct fire mode and/or that fire spin-stabilized projectiles (to account for the possibility of unstable projectile flight dynamics at high angles of fire).

ii) The following main instrumentation is identified:

- Meteorological soundings,
- Impact Point Measurements,
- Muzzle velocimeter,
- Doppler radar is required for base burn or assisted projectiles.
-

iii) Ground impact: The fall of shot method requires a minimum of 50 rounds per velocity zone (40 rounds for mortars) fired in 5 round groups at 5 quadrant elevations on a total of 10 occasions; 5 with one weapon / propellant lot combination and 5 with another. This design must be used when no Tracking Radar is available. In that case the design is limited to use with single trajectory phase projectiles. Table B.1 outlines this test design for artillery and naval weapons, while Table B.2 outlines this test design for mortars. The test is to be used to determine form factor, lift factor, delta time of flight (as defined in Annex H), PE_R, and PE_D (as defined in Annex I) A Doppler Radar or Tracking Radar should always be used if available. If propulsion performance fitting factors are to be determined then a Doppler radar must be used to track the motor burn phase.

iv) Air burst: The same test design may be used to estimate PE_{HOB} , PE_{FS}, $i_{submunition}$ for carrier rounds and submunition as well as pattern dimensions. Charge and quadrant elevation (QE) combinations are chosen to cover the operational time of flight spectrum from the lowest charge/low angle QE to the maximum charge/high angle QE in increments of approximately 20 seconds. Burst heights are chosen to insure all rounds will be air burst. These combinations may be different from those described in Tables B.1 and B.2.

v) This test design may also be used to determine aerodynamic data. In that case instrumented rounds must be fired according to national procedure. (e.g. Yaw and spin measurement).

vi) Figures B.1 and B.2 show the effects of changes to the total number of rounds per charge (50, 100, 150) and the number of rounds per group (5, 10, … 30) on the quality of the mean performance and dispersion estimates. For example, increasing the number of groups (decreasing the number of rounds per group for a fixed total number) improves the accuracy of the mean performance estimates (decreases the percentage of range interval containing the truth). However, decreasing the number of groups (using larger sample sizes per group) is desired to improve the dispersion estimates. These two opposing trends must be balanced to insure that both mean performance and dispersion requirements are met.

These graphs may be used to determine the required number of occasions and the number of rounds per occasion to obtain unbiased ballistic performance data. If smaller numbers of rounds or occasions are to be applied then a statistical analysis should be provided granting the ballistic performance data.

(1) Artillery, Naval Indirect Gunfire, and Mortars

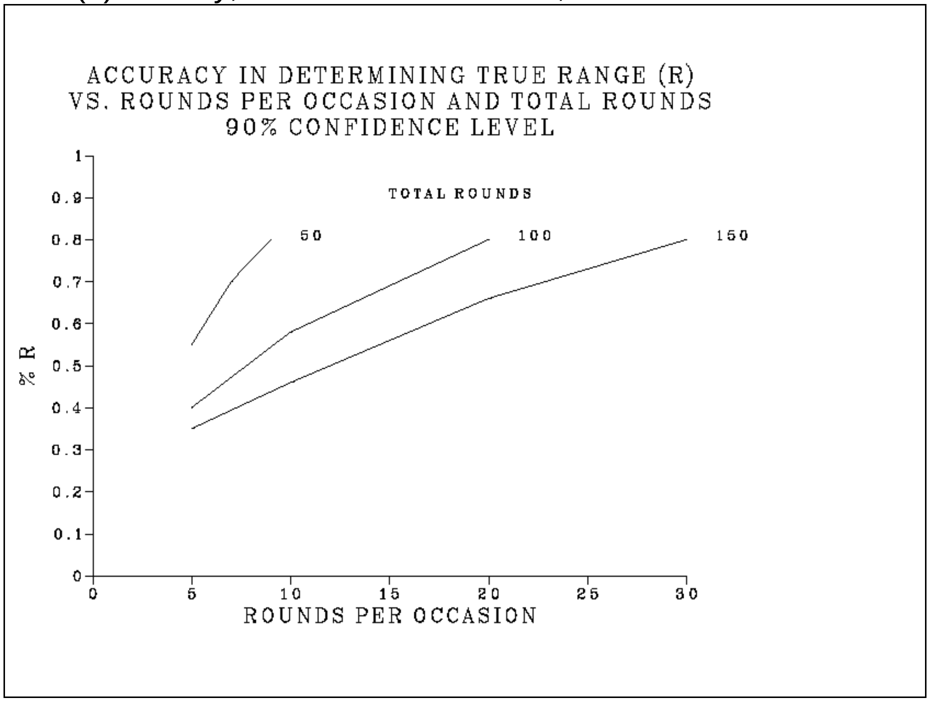

Figure B. 1 Accuracy in determining true range (R) vs. rounds per occasion and total rounds 90 % confidence level

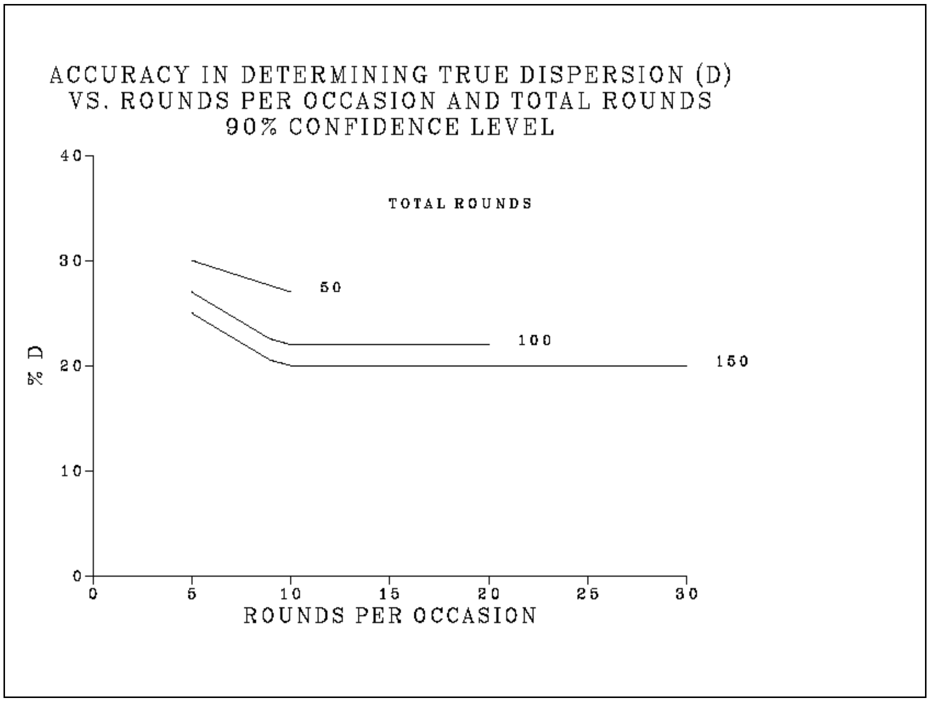

Figure B. 2 Accuracy in determining true dispersion (D) vs. rounds per occasion and total rounds 90 % confidence level

c) Vertical Target Test (Direct Fire)

Given the aerodynamic coefficients needed for the PM Model (see paragraph 1.c) and using estimates of the within group and between group variability of the ballistic factors:

i) The following main instrumentation is identified:

-Meteorological soundings,
-Surface meteorological measurements
-Target impact measurements,
-Muzzle velocimeter,
-Time of flight measurements,
-Downrange velocimeter.

ii) The target location is dependent on the type of projectile tested and its respective service range. At least two gun barrels are required. For each projectile type at least three occasions of 10 rounds must be fired from each barrel. This gives a minimum of 60 rounds needed per projectile type.

d) Wind conditions suitable for these findings are described in Annex D.

e) For munitions under 40mm, projectile and propellant used in the test are to be conditioned to 21° C for at least 2 hours immediately prior to firing. For munitions over 40mm, projectile and propellant used in the test are to be conditioned to 21° C for at least 24 hours immediately prior to firing.

3) AERODYNAMIC PERFORMANCE FIRING TEST DESIGN (COMPLETELY INSTRUMENTED FIRINGS METHOD)

a) This test design may be used to determine aerodynamic coefficients and ballistic performance (ballistic fitting factors and probable errors). However when used for ballistic performance without additional firings, then it should be statistically proved that the number of rounds and the number of occasions is sufficient to meet the uncertainty requirements in mean performance and dispersion.

b) The following main instrumentation is identified:

- Meteorological soundings (with surface meteorological measurements for direct fire),
- Impact measurements,
- Muzzle velocimeter,
- Doppler radar,

- Optical instrumentation,
- Yaw measurement system.

c) Given that aerodynamic forces and moments depend mainly on the Mach number and the yaw, the following trial plan must include these factors. In order to account for occasion to occasion variability of these forces and moments a minimum number of trials must also be determined to meet the required accuracy of the aerodynamics coefficients.

d) Artillery and Naval

i) For multi-charge weapons, firings must be carried out with sufficient charges to cover the Mach number region. As a minimum the number of charges chosen must cover the required Mach number region without leaving any gaps and must include the highest and lowest charges and an intermediate charge.

ii) Firings must be carried out with a sufficient number of elevations to cover the required yaw angle level. A minimum of five elevation angles is required.

iii) A minimum of 2 rounds for each chosen elevation / charges must be fired.

iv) For base burn and rocket assisted shells, supplementary parameters have to be determined.

(1) Firings must be carried out with an inert base burn or without base burn unit in the same way as described previously [a. to e.].

(2) Firing must be carried out with an active base burn unit conditioned at 21° in the same way as described previously [a. to e.]. Notice, that if the drag reduction is charge dependent, firings with active base burn unit at all charges are required.

(3) Firings with active base burn unit must be carried out at several conditioned temperatures. A minimum of three charges, five temperatures and two quadrant elevation angles is required.

v) Example firing test plans are given in the tables hereunder. The Standard Aerodynamic Firing Test Design (Table B.3) is applicable for unassisted projectiles and the base-burn and rocket assisted projectiles

Motor-Off and 21°C Motor-On aerodynamic trials. The Non-Standard Motor Temperature Aerodynamic Firing Test Design (Table B.4) is applicable for base-burn and rocket assisted projectiles for the Non-Standard Temperature Motor-On aerodynamic trials.

Table B.3: Standard Aerodynamic Firing Test Design.

Elevation	All Charges
400	2
600	2
800	1+1
1000	2
1150	1+1

Table B.4: Non-Standard Motor Temperature Aerodynamic Firing Test Design.

Temp (°C)	Elevation (mils)	All Charges
-40.0	600 800	2 2
-31.0	600 800	2 2
5.0	600 800	2 2
36.0	600 800	2 2
51.0	600 800	2 2
60.0	600 800	2 2

Notes: - The firings with cold projectiles in ambient atmosphere may result in unreliable drag results due to icing on the projectile.
- The motor temperature values are given as an example.

<u>In the tables given above</u> :
2: two identical rounds not fired consecutively.
1+1: One of the rounds can be equipped with a yaw measurement system.
In order to determine probable errors in quadrant elevation the following firing sequence is proposed: quadrant elevation fixed 6 rounds, one for each charge.

e) Mortars

i) For multi-charge weapons, firings must be carried out with sufficient charges to cover all the Mach number regions of interest. At a minimum the number of charges chosen must cover the required Mach number region without leaving any gaps and must include the highest and lowest charges and an intermediate charge.

ii) Firings must be carried out with a sufficient number of elevations to cover the required yaw angle level. A minimum of three elevation angles is required.

iii) An example firing test plan is given in the table hereunder.

Table B.5: Mortar Aerodynamic Firing Test Design.

Elevation	All Charges
800	2
1150	2
1500	1+1

In the table given above :
2: two identical rounds not fired consecutively.
1+1: One of the rounds can be equipped with a yaw measurement system.

f) Direct Fire

i) Firings must be carried out with a sufficient number of elevations to cover the required yaw angle level. A minimum of three elevation angles (ranges) are required.

ii) An example firing test plan is given in the table hereunder.

Table B.6: Direct Fire Aerodynamic Firing Test Design.

Range	Rounds Fired
Middle Effective	5
Maximum Effective	5*
Maximum Safe Range	5*

In the table given above :
5: five identical rounds not fired consecutively.
5*: One or more of the five rounds can be equipped with a yaw measurement system as described in national procedures.
The term Maximum Effective Range used here is the range up to which the system is designed to effectively engage point and/or area targets.

The term Maximum Safe Range used here is the estimated maximum range to which the projectile is capable of achieving under standard conditions, typically by means of firing at quadrant elevations much greater than those used in direct fire systems.

4) DATA AND MEASUREMENTS

Data required for each firing sequence: Weapon description (Model No., barrel serial number, estimate of gun remaining life, length of the barrel, etc.)

a) Data and accuracy of measurements for a ballistic performance test design ([..] = one standard deviation for each shell fired including warmer rounds).

i) Meteorological soundings and surface conditions including ambient temperature (see Annex D).

ii) Firing time (of day) [0.5 min].

iii) Latitude [0.25°].

iv) Indirect Fire

(1) Point of impact (intersection of measurements by theodolites / Laser rangefinders) [5m].

(2) Time of flight / fuze function time, if applicable time of illumination and burn time (Infrared Sensor / Video / Optronic Tracking / Stopwatch) [0.05 sec].

(3) Projectile mass [0.1%] and axial moment of inertia [0.5%].

(4) Muzzle velocity (instrumentation conforming to STANAG 4114) [0.1%].

(5) Propellant temperature (Thermometer) [1° C].

(6) Drag (C_d) (Doppler Radar).

(7) Quadrant elevation [0.5 mil].

(8) Azimuth [0.2 mil].

v) Direct Fire

(1) Height of impact area [1 m]

(2) Measurements on vertical target [10 mm]

(3) Time of flight [0.001 sec]

(4) Time events along trajectory including fuze function time [0.05 sec]

(5) Projectile mass [0.1%] and axial moment of inertia [0.5%]

(6) Muzzle velocity [0.05% or 0.25 m/s whichever is less]

(7) Temperature measurements [0.35° C]

(6) Drag (C_d) (Doppler Radar).

(9) Elevation and azimuth angles [0.025 mil]

(10) Azimuth of line of fire [0.1 mil]

b) Instrumentation and/or measurements optional for a Ballistic Performance and required for an Aerodynamic Firing Test Design are:

i) Complete trajectory vs. time (Trajectory Radar).

ii) Yaw angle (Yaw measurement system).

iii) Projectile Spin (Yaw measurement system, Doppler Radar).

c) Optional exterior ballistic instrumentation and/or measurements:

i) Optronic Tracking.

ii) Submunition performance (Video).

iii) Jump (e.g. Cards, Optical tracking).

iv) Droop (mechanical measurements).

v) Other instrumented fuzes/projectiles (e.g. GPS sonde).

d) Optional internal ballistic instrumentation and/or measurements:

i) Maximum pressure (Piezo / Crusher Gauge).

ii) In-bore projectile velocity.

iii) Recoil.

iv) Gun barrel heating.

5) TEST DESIGN FOR MUZZLE VELOCITY VS. TUBE WEAR FOR ARTILLERY AND NAVAL SYSTEMS (OPTIONAL)

In order to determine the change in muzzle velocity (MV) due to tube wear the following test procedure should be included as part of the national cannon wear test for each propellant geometry, propellant type and rotating band design combination. For further information see Annex F.

a) Fire at least 5 rounds at standard propellant temperature (21 °C).

b) Conduct firing at approximately each quarter of remaining tube wear life (100%, 75%, 50%, 25%, 0%).

c) Fire at least 1 charge (velocity zone) from each propellant type and geometry but always include the maximum charge for the propellant/gun combination.

d) Measure the muzzle velocity and chamber pressure for each test round using NATO approved velocimeters and crusher gauges.

e) Calculate the average muzzle velocity of each test group and calculate the difference between the average MV at each quarter of remaining cannon life and its corresponding value for the new cannon. From these differences the MV versus tube wear relationship can be estimated.

f) Fit the resulting MV variation (MVV) versus tube wear data as:

$$MVV = a_0 + a_1(EFC) + a_2(EFC)^2 + a_3(EFC)^3$$

g) Record the observed MVV versus tube wear data and the fitted values in tabular or graphical form in Annex J, Test Data summary.

Note: The same projectile and propellant lot should be used throughout the test.

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ANNEX C FIRING TEST DATA ANALYSIS

1) DATA REDUCTION FOR BALLISTIC PERFORMANCE FIRING TEST

a) Ballistic data

For each 5 or 10 round group of the basic ballistic performance test design, the MPM or PM model with previously determined aerodynamic coefficients is used with the measured initial conditions and meteorological data to match the observed impact data (range, deflection and time of flight) using iterative steps adjusting the appropriate fitting factor. When motor performance is required the appropriate fitting factors are used to match the measured radial velocity and/or derived drag data during burning in addition to the final impact data. The resulting factors are then fitted using regression techniques to estimate the relationship with the QE. The sample sizes are chosen to achieve mean performance estimates to within 0.5% of the true range at 90% confidence.

The test data summary will be a tabular or graphical display of the observed fitting factors versus elevation for each occasion fired along with the values calculated using regression results.

b) Probable errors

For each 5 or 10 round group out of the basic ballistic performance test design, calculate the mean and probable error about that mean in range and deflection (or in vertical and horizontal miss distance for a vertical target test). The probable errors are fitted using regression techniques to the forms shown in Annex I. In addition the PE in muzzle velocity and PE in form factor for each group (within a charge) are pooled together in a weighted average (based on number of rounds per occasion) to estimate the PE_{MV} and PE_{i} to be used in the error budget approach. For the assisted projectiles, the PE in the motor performance fitting factors are analyzed in a similar manner. The PE_{FS} and PE_{HOB} are estimated from the air burst test using similar methods.

The test data summary will be a tabular or graphical display of the observed PE values for each occasion fired along with the values calculated from regression results.

Note: In all the above analyses outlier tests (as defined in STANAG 4106) are applied and anomalous data removed. Data removed in this manner shall be part of the overall data presentation (Annex J). When possible, variances (PE's) are tested for equality before pooling.

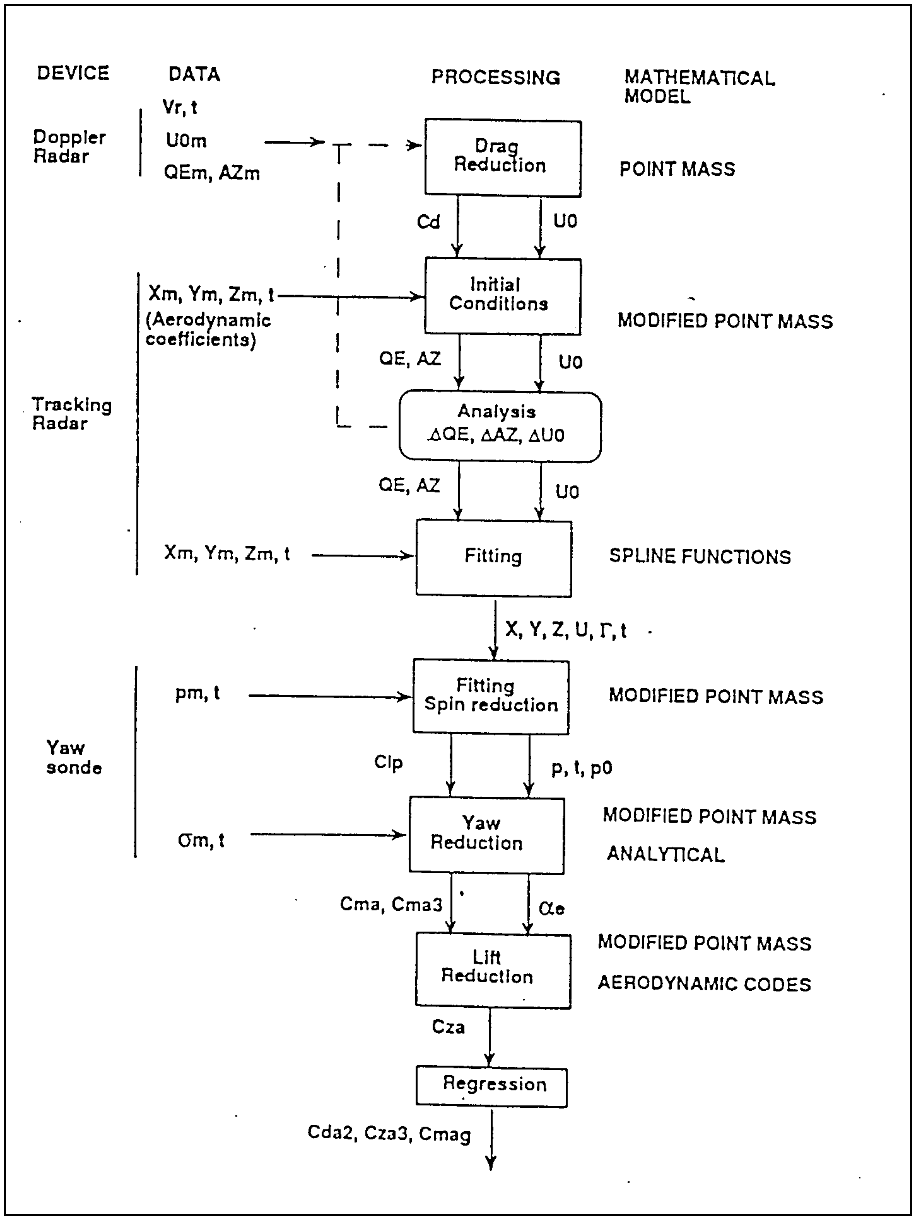
2) DATA REDUCTION FOR AERODYNAMIC PERFORMANCE

a) Introduction

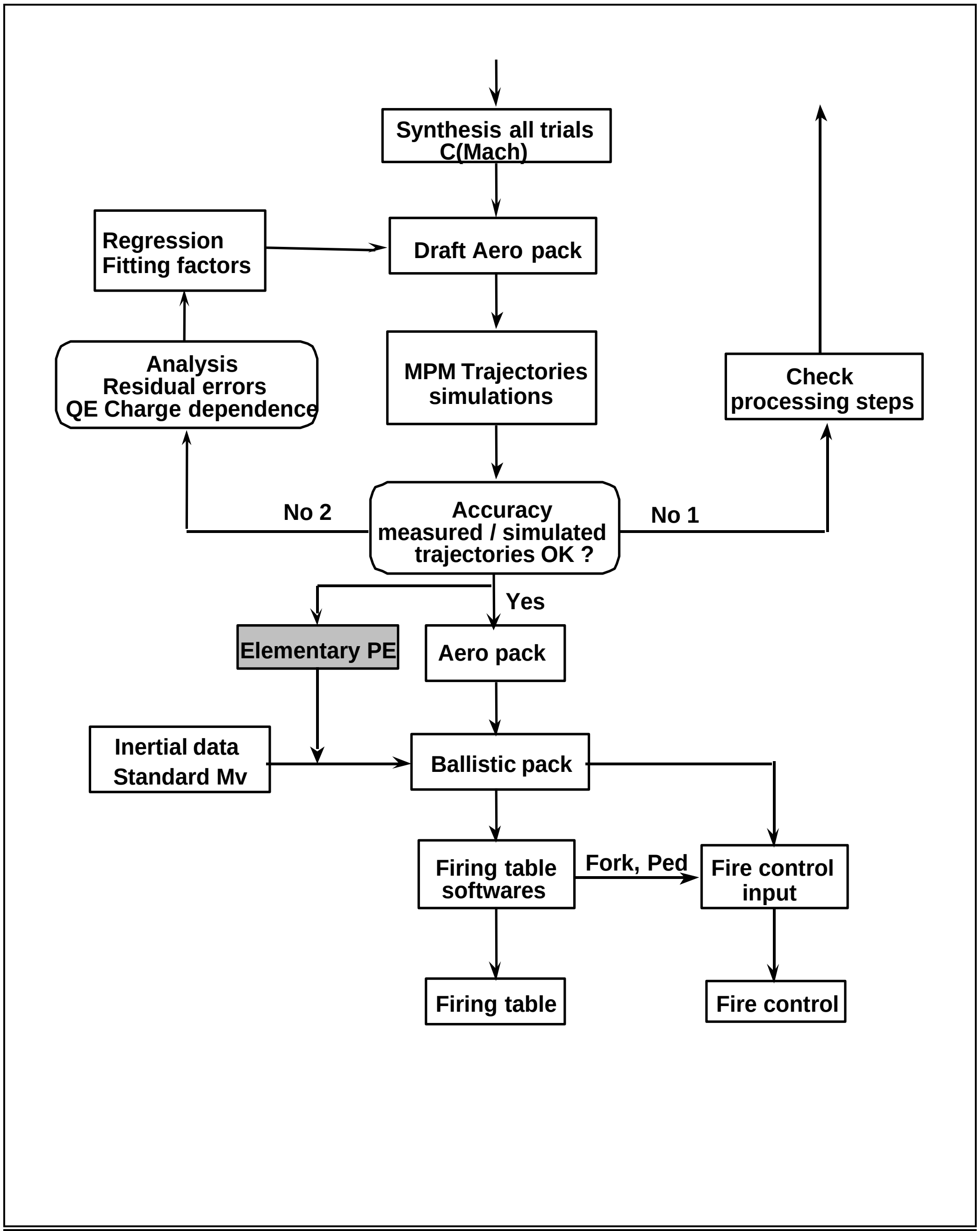
This example process may be used to obtain aerodynamic coefficients, ballistics fitting factors and ballistic precision using complete instrumented Firings Method

The data analysis is conducted in successive steps ordered as shown in flow chart **Part 1**. The methods used at each step are mainly of three types: fitting by Spline function, MPM or PM iterative adjustment, and MPM inversion. Spline function is a useful tool for data fusion first to compact numerous data in a few numbers of polynomial coefficients, secondly to synchronize easily the fitted data. The successive steps are connected in such an order to insure that all data needed at one step are results from the previous ones. In the flow chart **Part 2** the results from all firings are checked first by the analysis of the differences between simulated trajectory using the resulting aerodynamic coefficients and measured trajectory. Explanation of inaccuracy is first performed in reviewing all the data reduction process (branch N° 1: outlier measurements, wrong input data…). Then the analysis permits to refine all aerodynamic coefficients (yaw dependence, limits of Mach range …), determine the fitting factors if necessary and establish the error budget (as defined in Annex I). At this step the available aero pack and error budget completed by inertial data and standard muzzle velocity are used for firings table calculation and are included in fire control input database.

French (DGA/ETBS) example for data analysis of aerodynamics Firing Test (**Part 1**)



French (DGA/ETBS) example for data analysis of aerodynamics Firing Test (**Part 2**)



b) Aerodynamic and ballistic data

Aerodynamic coefficients and fitting factors are determined using measurements made on full-scale projectiles in real firing conditions.

- Drag coefficients are determined using a mathematical model based on the Point Mass Model using Doppler radar measurements.
- Spin damping and overturning moment coefficients are determined using a mathematical model based on MPM and an analytical formulation of yaw associated with yaw and trajectory radar measurements.
- Lift coefficients are determined using a mathematical model based on MPM associated with trajectory measurements.
- All these coefficients associated with second order or third order and Magnus coefficients are then improved using comparisons versus time between measured and simulated trajectories and velocities. In order to further improve residual range, drift and time of flight between measured and computed trajectories fitting factors can be used.
- For base burn projectiles the charge and temperature dependent fitting factor f(iBB,MT) is determined using Doppler and trajectory radar measurements versus time during the base burn phase.

c) Probable errors

Probable errors in range and deflection (or in the vertical/height and horizontal/width for a vertical target test) are determined from the error budget. The quantification of the error budget parameters is based on firings. They are determined according the procedures defined in Annex I.

- PE_{MV} should be determined per charge by analysis of the dispersion of the muzzle velocity data collected from all dynamic firings. All measured velocities should be corrected to standard conditions. Extreme condition firings may be excluded.

- PE_{QE} and PE_{AZ} are determined by analysis of the initial trajectory data (line of departure).

- PE_i and PE_{f_L} are determined by analysis of the trajectory data of all firings in the aerodynamic performance firing test.

- PE_m is determined by weighing all projectiles used in all tests.

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ANNEX D METEOROLOGICAL CONDITIONS

METEOROLOGICAL LIMITS

1) METEOROLOGICAL LIMITS - INDIRECT FIRE

a) It is a requirement to take meteorological data, both at the surface and aloft to 300 m above the maximum ordinate, preferably 1000 m above. Measurements should be taken for wind data on an hourly basis, preferably half-hourly. Air pressure, temperature and humidity data measurements should be taken at hour-and-a-half intervals, preferably hourly. Data gathering should begin before the first round is fired and end after the last round. The meteorological measurements aloft are considered valid to a maximum range of 30 km from the meteorological measurement equipment, the meteorological station. The total of all meteorological measurements must encompass the entire trajectory. Surface meteorological data at the weapon position are measured as required; additional low level wind data may be required in the impact area. When detecting projectiles that eject a payload during flight, the office supplying the firing plan will specify the maximum required altitude for wind measurements and the allowable wind speed limits.

b) Alternatively, when a national meteorological service or Weather Analysis Center can supply meteorological data from other sources and/or techniques (e.g. forecasting) as good as or better than soundings then it may be used.

c) High steady winds when firing high velocity zones are usually acceptable. Firing during very gusty winds or during frontal passages is unacceptable at any velocity zone. Consequently, range firing should not be attempted when one of the following conditions exists:

i) Average surface wind speed exceeds 10 m/s (20 knots),

ii) Wind speed between 300 m and the maximum ordinate changes by more than 7.5 m/s (15 knots) when either:

(1) Comparing the same discrete altitude levels (as defined in STANAG 4082) from two consecutive meteorological messages, or

(2) Comparing consecutive discrete altitude levels (STANAG 4082) of the same meteorological messages.

iii) Wind direction between 300 m and the maximum ordinate changes by more than 800 mils (45 °) when either:

(1) Comparing the same discrete altitude levels (STANAG 4082) from two consecutive meteorological messages, or

(2) Comparing consecutive discrete altitude levels (STANAG 4082) of the same meteorological messages.

d) If the wind speed at any discrete altitude level (STANAG 4082) is less than 2.5 m/s (5 knots), changes in wind direction may be disregarded and the range firing may be continued.

2) METEOROLOGICAL LIMITS - DIRECT FIRE

a) Surface meteorological data, such as wind speed and direction, air pressure, air temperature, and humidity, should be collected at the weapon position and the target. Additional surface meteorological data collected at one-third range intervals is recommended. Surface meteorological data should be taken prior to every shot. However, if such sampling is not feasible data should be collected at intervals of least every five minutes. For tests with trajectories having a maximum ordinate of over ten meters meteorological data should be collected aloft to the maximum ordinate, and preferably to ten meters over the maximum ordinate. Measurements should be taken for wind data on an hourly basis, preferably half-hourly. Air pressure, temperature and humidity data measurements should be taken at hour-and-a-half intervals, preferably hourly. Data gathering should begin before the first round is fired and end after the last round.

b) Alternatively, when a national meteorological service or Weather Analysis Center can supply meteorological data from other sources and/or techniques (e.g. forecasting) as good as or better than soundings then it may be used. However, this type of data collection should not be substituted for surface conditions between the gun and target.

c) Firing during very gusty winds or during frontal passages is not recommended. Consequently, range firing should not be attempted when one of the following conditions exists:

i) Average surface wind speed exceeds 5 m/s (10 knots).

ii) Wind gusts vary the wind speed by more than 2.5 m/s (5 knots).

d) If the wind speed at any discrete altitude level (STANAG 4082) is less than 2.5 m/s (5 knots), changes in wind direction may be disregarded and the range firing may be continued.

3) METEOROLOGICAL VERIFICATION

Surface and aloft meteorological measurements should be taken before proceeding with the firing plan to ensure that the meteorological conditions are satisfactory.

4) METEOROLOGICAL DATA REQUIRED

The following data should be determined for range firing tests:

a) Surface meteorological data at the gun position and at the meteorological station: surface air pressure, temperature, humidity, wind speed and direction;

b) Meteorological data aloft should include air pressure, temperature and humidity, wind speed and direction. It should be recorded at least at the heights defined by the zones in a Standard Artillery Computer Meteorological Message (STANAG 4082), preferably at 100 m intervals from gun altitude to the previously specified point aloft of maximum ordinate.

c) The wind direction should define the direction from which the wind is blowing, for example, a wind direction of “0” indicates a wind blowing from the North. Reference should be made whether the given altitude means above mean sea level or above the surface area level and whether North means Geographic, Grid or Magnetic North.

d) The required tolerances for meteorological data aloft are given in table D.1.

Table D.1: Required tolerances for meteorological data aloft.

Measurement	Units	Tolerance
Date and time	min.	1
Height	m	5
Air pressure	hPa	1
Air temperature	°C	1
Humidity	%RH	5
Wind speed	m/s	1
Wind direction	mils	17

e) The coordinates of the meteorological station should be recorded, including the altitude above mean sea level, giving sufficient information to relate the position of the meteorological station with the gun and the trajectory of the projectile

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ANNEX E PHYSICAL AND MOTOR DATA

1) All data applicable for the assisted propulsion and for submunitions are considered to be physical data unless clearly appointed as aerodynamic data, fitting factor or probable error data even when this is not a true physical parameter. Some of these data are determined using firing tests specified in Annex B.

2) All data listed hereunder are to be determined by national procedures if not defined in this STANAG. Standard projectile physical data are listed in table E.1; additional data for submunitions are listed in table E.2; standard weapon physical data are listed in table E.3; additional data for projectiles with bourrelet nubs are listed in table E.4; and additional data for assisted projectiles are listed in table E.5.

Table E.1: Standard Projectile Physical Data.

Parameter	Symbol	Unit	Weapon Type[1]	Trajectory Model[2]
Reference initial mass of fuzed projectile	m_r	kg	A,M,DF,N	PM,MPM
Weight squares (minimum/standard/maximum)		-	A,M(opt)	MPM
Mass difference between weight squares	Δm_n	kg	A,M(opt)	MPM
Reference fuze mass	m_{fuze}	kg	A,M(opt)	MPM
Reference diameter of projectile	D	m	A,M,DF,N	PM,MPM
Initial axial moment of inertia	I_{X_0}	kg·m^2	A,M,DF,N	MPM
Initial spin of projectile wrt ground (or rifling twist near muzzle)	P_0	cal/rev	A,M,DF,N	PM(opt),MPM
Mass of tracer element (optional)	m_{tracer}	kg	DF	PM,MPM

[1]A, M, DF, and N indicate Artillery, Mortars, Direct Fire, and Naval weapons respectively
[2]PM and MPM indicate point mass and modified point mass trajectory models respectively

Table E.2: Additional Data for Submunitions.

Parameter	Symbol	Unit
Mass of submunition unit	m_{sn}	kg
Reference submunition cross sectional area	S_{sn}	m^2
Ejection velocity	$\Delta \vec{u}_s$	m/s
Height of Burst	HOB	m
Time of Fall	T_{f_s}	s

Table E.3: Standard Weapon Physical Data.

Parameter	Symbol	Unit
Distance from trunnion to muzzle		m
Remaining tube life		-
Angle of cant of trunnion after weapon is seated		mils
Stargage Data[a]		m

[a]Bore diameter measurements according to Annex F

Artillery and Naval Guns:

Table E.4: Additional Data for Projectiles with Bourrelet Nubs.

Parameter	Symbol	Unit
Angle of nubs wrt projectile axis and nub geometrical center.	δ	rad

Table E.5: Additional Data for Assisted Projectiles.

Parameter	Symbol	Unit	Model[a]
Diameter of projectile base	d_b	m	B1,B2
Exit area of motor jet	A_e	m^2	R1,R2[b]
Distance of center of mass from nose, initially	X_{CG_0}	m	B1,B2,R1,R2
Distance of center of mass from nose at burn out	X_{CG_B}	m	B1,B2,R1,R2
Fuzed projectile mass at burn out	m_b	kg	B1,B2,R1,R2
Mass of ignition delay element	m_{DI}	kg	R1,R2
Mass of delay obturator	m_{ob}	kg	R1
Mass of motor fuel	m_f	kg	B1,R1,R2
Mass of motor fuel burnt in the barrel	m_{CB_0}	kg	B1
Reference mass flow rate of motor fuel	$\dot{m}_f^*$	kg/s	R2
Minimum mass flow rate of motor fuel for air pressure term	$\dot{m}_p$	kg/s	R2
Density of base-burn motor fuel	ρ_p	kg/m^3	B1
Base-burn motor fuel injection parameter for optimum efficiency	I_0	-	B1
Specific impulse of motor fuel	I_{SP}	N·s/kg	R1,R2
Axial moment of inertia at burnout	I_{X_B}	$kg \cdot m^2$	R1,R2
Standard time of rocket motor burnout	$t_{B_{ST}}$	s	R1,R2
Standard time of rocket motor ignition delay	$t_{DI_{ST}}$	s	R1,R2
Standard thrust	T_{ST}	N	R1,R2
Combustion area of base-burn motor fuel	SC	m^2	
Change in non dimensional base pressure for a change in the base-burn injection parameter	$\frac{\partial BP}{\partial I}$	-	B2
Combustion rate of base-burn motor fuel on strand burner	V_{C_0}	m/s	B1
Base-burn motor temperature fuel burning coefficient	β	-	B1
Exponent in burning rate versus pressure	n		B1
Constant in burning rate versus pressure	k		B1

[a] B1, B2, R1 and R2 indicate Base-Burn and Rocket Assisted Projectile methods 1 and 2 defined in STANAG 4355
[b] R2 may use A_e as fitting factor

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ANNEX F INTERNAL BALLISTIC DATA

1) INTERNAL BALLISTIC DATA CONCERNS THE FOLLOWING PARAMETERS:

a) Indirect Fire Systems

i) Standard Muzzle Velocity for Weapon/Projectile/Propellant/Charge being tested
ii) Muzzle Velocity Correction for Propellant Temperature
iii) Muzzle Velocity Correction for Projectile Mass (n-factor)
iv) Muzzle Velocity Loss for Tube Wear (optional)
v) In-bore Internal Ballistic Data (optional)

b) Direct Fire Systems

i) Standard Muzzle Velocity for Weapon/Projectile/Propellant being tested
ii) Muzzle Velocity Correction for Propellant Temperature
iii) Muzzle Velocity Loss for Tube Wear (optional)
iv) In-bore Internal Ballistic Data (optional)

2) STANDARD MUZZLE VELOCITIES WILL BE DEFINED USING THE FOLLOWING PROCEDURES:

a) Indirect Fire Systems

i) If the propelling charge system is to be adjusted to existing national or international standard muzzle velocities then STANAG 4568 applies.
ii) If Fire Control Inputs exist for the weapon/propelling charge system for a different projectile then the existing standard muzzle velocities of the reference projectile will be converted to the new configuration.
iii) If none of the above procedures is applicable then the standard muzzle velocity is to be determined from dynamic firing results.

b) Direct Fire Systems

iv) If none of the above procedures is applicable then the standard muzzle velocity is to be determined from dynamic firing results.

3) CONVERSION OF STANDARD MUZZLE VELOCITIES FROM EXISTING FIRE CONTROL INPUTS

If Fire Control for the weapon/propellant system already exists for a reference system then the muzzle velocity effect (e.g. different projectile mass, rotating band, recoil system, tube length, tube friction, rifling and/or chamber volume) can be theoretically calculated using the interior ballistic simulation model defined in STANAG 4367. The theoretical standard muzzle velocity of the new configuration is the standard muzzle velocity of the reference corrected for the muzzle velocity effect. For indirect fire systems, muzzle velocities gathered during dynamic firings, corrected to standard conditions (for example zero gun wear, standard projectile mass and standard propellant temperature), may be tested using the statistical procedures defined in STANAG 4106. If acceptable agreement between the expected and the experimental muzzle velocity effect is achieved then the theoretical standard muzzle velocity is validated.

4) DETERMINATION OF STANDARD MUZZLE VELOCITY FROM FIRING RESULTS

For all propellants/charges the standard muzzle velocity should be determined by analysis of data collected from all dynamic firings. All measured velocities should be corrected to standard conditions (for example zero gun wear, standard projectile mass and standard propellant temperature). Extreme condition firings may be excluded. If possible, it is recommended to fire reference projectile rounds during all firings to reduce occasion-to-occasion and weapon-to-weapon effects. At least two and preferably five weapons, in first quarter of remaining life, should be used in the firings. The muzzle velocity dispersion from these tests is to be determined, however for service rounds the muzzle velocity error budget should incorporate the projectile mass, propellant temperature, propellant lot and tube wear differences. For indirect fire systems, the standard velocity of a weapon/-ammunition configuration can also be established during trials for the determination of the propellant charge weight as defined in STANAG 4568.

5) DETERMINATION OF MUZZLE VELOCITY CORRECTIONS FOR PROPELLANT TEMPERATURE (MVCPT)

When a new propellant/charge is developed, the MVCPT are to be determined from firings between lowest and highest operational temperatures. It should be checked whether or not MVCPT are projectile dependent. MVCPT may be given as a polynomial in cubic terms, however if only two non-standard temperatures are tested, then no more than second degree polynomial apply and a linear form is recommended. MVCPT may vary with propellant/projectile and/or type/manufacturer and, if so, the charge must be uniquely denoted. The same firings should be used to calibrate the interior ballistic model (see STANAG 4367) to match the chamber pressures and muzzle velocities recorded at the chosen propellant temperatures. Once this reference model for this new propelling charge is established then the MVCPT can be theoretically predicted for other but similar projectile and weapon configurations.

The following firing test procedures may be used to evaluate MVCPT.

a) Since range need not be recorded, any angle of elevation, convenient for the firing, can be selected.

b) The weapon (tube/barrel) used in the test has 75% or better remaining life.

c) The firings are carried out at standard temperature (21 °C) and at least at the lowest and highest operational temperatures (e.g. -32°C /+43°C). Propellant burning behavior at extreme temperatures (e.g. -40°C /+63°C) might not represent the burning behavior at operational temperatures and therefore are discouraged.

d) For weapon systems above 40mm, the projectiles and propellant used in the test are conditioned at the test temperatures for at least 24 hours immediately prior to the firing according to STANAG 4568. For smaller caliber systems, the projectiles and propellant used in the test are conditioned at the test temperatures for at least 2 hours immediately prior to the firing.

e) For multi-charge systems, the firings are carried out with all charges.

f) Rounds are fired alternately at each temperature in the order 2W-k*(3H-2S-3L-2H-3S-2L); where "W" is a warmer round, "H" "S" and "L" are high, standard and low temperature rounds and "k" is the number of times the sequence will be fired (≥ 1). When cubic terms are to be calibrated then additional temperatures are incorporated (e.g. 3H-2I_H-3S-2I_L-3L-2H-3I_H-2S-3I_L-2L); where "I_H" and "I_L" are high and low intermediate temperatures.

6) IN-BORE INTERNAL BALLISTIC DATA (OPTIONAL).

These data are not part of Fire Control Inputs. However validated internal ballistic inputs are needed to perform the internal ballistic simulations described in STANAG 4367. To create these data in-bore measurement results from range and/or system safety firing tests may be added to the Test Data Summary. This concerns at least the maximum chamber pressure or the breech pressure versus time and preferably in-bore projectile velocity, heat transfer to gun barrel and recoil. Alternatively, internal ballistic data may be exchanged as an input file for the IBHVG2 code.

<u>Projectiles incorporating multiple weight zones (i.e. – square weights):</u>

7) DETERMINATION OF MUZZLE VELOCITY CORRECTION FOR PROJECTILE MASS (N-FACTOR).

The n-factor is to be theoretically predicted using the interior ballistic simulation model defined in STANAG 4367. If considered necessary, a small check firing may be conducted to substantiate the theoretically predicted n-factors. The following procedure may be used to conduct this check fire.

a) Since range need not be recorded, any angle of elevation, convenient for the firing, can be selected.

b) The cannon used in the test has 75% or better remaining life.

c) The projectiles and propellant used in the test are conditioned to 21 °C for at least 24 hours immediately prior to the firing.

d) Preferably, two equally sized series of projectiles are prepared to be heavier and lighter than the standard projectile mass. If possible the mass differences within each series are less than 0.1% and the mean masses of the series differ about 10 % (± 5% from m_s); the moments of inertia and the centers of gravity should stay unaltered. At least 7 rounds per series are fired alternately. The experimental n-factor is found by the following formula:

$$n_{\exp} = \frac{m_s}{v_s} * \frac{\Delta v}{\Delta m} = \frac{m_s}{v_s} * \frac{v_H - v_L}{m_H - m_L}$$

where:
- v_H = mean muzzle velocity of heavy series
- v_L = mean muzzle velocity of light series
- m_H = mean projectile mass of heavy series
- m_L = mean projectile mass of light series

e) Alternatively when the light and heavy series of projectiles are not prepared but selected from the available stock then the sample size per series should be at least ten. Analysis of firing data will make use of the following formula:

$$n_{\exp} = \frac{m_s}{v_s} * \frac{\sum_{i=1}^{k}(\Delta v_i \Delta m_i)}{\sum_{i=1}^{k}(\Delta m_i)^2}$$

where:
- Δv_i = v_{H_i} - v_{L_i}
- Δm_i = m_{H_i} - m_{L_i}
- v_{H_i} = muzzle velocity of i-th heavy round
- v_{L_i} = muzzle velocity of i-th light round
- m_{H_i} = projectile mass of i-th heavy round
- m_{L_i} = projectile mass of i-th light round

f) Acceptable agreement between the theoretically predicted and the experimentally determined n-factor will be achieved if the “t-test” shows no significant difference between them at the 95% confidence level. The “t-test” is described in STANAG 4106. Annex C. If there is no agreement at this level, additional tests and/or analysis should be conducted.

<u>Artillery, Naval Guns, Tanks, and Medium Caliber Cannons:</u>

8) DETERMINATION OF MUZZLE VELOCITY LOSS FOR TUBE WEAR (OPTIONAL).

The process of erosion removes metal from the bore surface of a cannon by the movement of hot gases and residues generated from the burning of the propellant as well as by the passing of the projectile through the bore. The wear life (given in maximum permissible wear diameter) and the fatigue life are defined at gun tube design. The determination of the number of design full charge service rounds to wear life and the muzzle velocity loss as a function of the wear diameter are part of the classification of the gun tube. Wear and fatigue life testing are to be performed by national procedures; a competent method to perform these tests for indirect fire systems can be found in STANAG 4568. For all designed propellant charges a wear equivalent full charge (EFC) factor is to be appointed (design full charge = 1.00).

There may be significant different wear between different types of projectiles and/or rotating bands. If wear data for the gun tube already exists then additional wear EFC factors are only required when the charge system significantly differs to the design charge system with regard to muzzle velocity level, propellant flame temperature and/or chemical composition of the reactive (oxidizing) gasses. The number of rounds to establish a wear EFC factor should be at least one quarter of the number of design full charge service rounds (for wear lower than EFC) or equivalent to one quarter of wear life (for wear higher than EFC).

The change in muzzle velocity as a cannon wears out depends on the propellant geometry, propellant type (chemical composition) and the rotating band design. As part of the national cannon wear testing procedure it is recommended that firings are conducted for at least one charge (MV) corresponding to each different propellant geometry and type and rotating band design according to the plan described in Annex B.

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ANNEX G AERODYNAMIC COEFFICIENTS

1) Aerodynamic Coefficients are dimensionless and given as functions of Mach number. These functions are in the form of consecutive polynomials of fourth degree or less defined over regions of Mach number, from $M_{MAX_{i-1}}$ up to and including M_{MAX_i}. The upper limit of the highest interval should be higher than the Mach number corresponding to the maximum possible muzzle velocity. Each aerodynamic coefficient is described by a series of polynomials of the form:

$$C_i = a_{0,i} + a_{1,i}M + a_{2,i}M^2 + a_{3,i}M^3 + a_{4,i}M^4$$

where C_i is a particular aerodynamic coefficient and M is Mach number.

The series of polynomials must be continuous and, for third or fourth degree polynomials, preferably differentiable at connecting breakpoints (using spline functions).

NATO Fire Control Systems use the C-system of aerodynamic coefficients. The K-system, also known as aeroballistic coefficients, is obsolete and should be transferred to the C-system using the C-to-K relationship constants defined in STANAG 4355 part III.

2) In decreasing order of preference, aerodynamic coefficients may be determined by:

a) Experimental measuring techniques:

i) Firing Tests (using yaw measuring system);
ii) Aeroballistic Range (or Spark Range) Tests;
iii) Wind Tunnel Tests;

b) Software simulation techniques:

i) Computational Fluid Dynamic Code (solving Navier-Stokes equations);
ii) Semi-Empirical Interpolation Code (interpolating among simplified theory or tabulated aerodynamic data for typical projectile designs and shapes).

3) Computer simulations are highly cost effective and generally accurate for conventional projectiles. Using computer simulations to draft aerodynamic coefficients requires validation of the pack using firing test results for determination of fitting factors. If the fitting factors are out of range or in poor correlation ($R^2 < 0.25$) then the drafted aerodynamic pack may not be validated, even when this is expected to be due to experimental conditions.

4) Preferably, all experimentally determined aerodynamic coefficients are included in the Test Data Summary (Annex J).

5) Drag Coefficient (C_D) obtained from Doppler radar measurements is total drag. It may be used directly in the Point Mass Trajectory Model and for the determination of Probable Errors but should not be used as Zero Yaw Drag Coefficient (C_{D_0}) in the Modified Point Mass Trajectory Model. Nevertheless, at the beginning of the trajectory, when the yaw is low, total drag can be assimilated to C_{D_0} drag.

Modified Point Mass

6) The following Aerodynamic Coefficients are used in the Modified Point Mass Model. The basic MPM aerodynamic coefficients are listed in table G.1; the additional terms for projectiles with bourrelet nubs are listed in table G.2; the additional terms for assisted projectiles are listed in table G.3 and additional terms for submunitions are listed in table G.4.

Table G.1: Basic MPM aerodynamic coefficients

Parameter	Symbol	Unit
Zero yaw drag coefficient	C_{D_0}	-
Quadratic yaw drag coefficient	$C_{D_{\alpha^2}}$	1/rad^2
Lift force coefficient	C_{L_α}	1/rad
Cubic lift force coefficient	$C_{L_{\alpha^3}}$	1/rad^3
Overturning moment coefficient for initial fuzed projectile	C_{M_α}	1/rad
Cubic overturning moment coefficient	$C_{M_{\alpha^3}}$	1/rad^3
Magnus force coefficient	$C_{N_{p\alpha}}, C_{Mag}$	1/rad^2
Spin damping moment coefficient	C_{l_p}, C_{spin}	-

Table G.2: Additional terms for projectiles with bourrelet nubs

Parameter	Symbol	Unit
Spin moment coefficient, due to canted bourrelet nubs, at zero spin	C_{l_δ}	1/rad
Side force coefficient, due to canted bourrelet nubs, at zero spin	C_{N_δ}	1/rad

Table G.3: Additional terms for assisted projectiles

Additional terms for assisted projectiles	Symbol	Unit	Model[a]
Zero yaw drag coefficient (thrust on)	$C_{D_{0_T}}$	-	R1+R2
Change in non dimensional base pressure for a change in the base-burn injection parameter (see Motor Data)	$\frac{\partial BP}{\partial I}$	-	B2
Drag reduction coefficient during base-burn motor burning	$C_{x_{BB}}$	-	B1

(a) Where B1, B2, R1and R2 indicate the Base-Burn or Rocket Assisted Projectile methods 1and 2 defined in STANAG 4355

Table G.4: Additional terms for submunitions

Additional terms for submunitions	Symbol	Unit
Drag coefficient of submunition	$C_{D_{sn}}$	-
Spin damping coefficient of submunition (optional)	$C_{spin_{sn}}$	-

Point Mass

7) The Point Mass Model uses the (total) Drag Coefficient. This includes the effect of a tracer on the drag (if applicable). The Point Mass Model may also use the Spin Damping Moment Coefficient to simulate the spin rate of projectiles or submunitions for the purpose of turn counting, etc.

Table G.5: PM aerodynamic coefficients

Parameter	Symbol	Unit
Drag coefficient	C_D	-
Spin damping moment coefficient (optional)	C_{l_p}, C_{spin}	-

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ANNEX H FITTING AND CORRECTION FACTORS

1) The determination of fitting factors in an Aerodynamic Firing Test may be part of the data reduction for the aerodynamic coefficients. In a Ballistic Performance Firing Test all aerodynamic coefficients must be drafted prior to the firing test. If the fitting factors are out of limits, inconsistent at different occasions, or in poor correlation then a drafted aerodynamic pack may not be validated, even when this is expected to be due to experimental conditions.

2) The degree of a polynomial fitting function may be determined from the correlation coefficient. If the correlation is very poor for all polynomial degrees ($R^2 < 0.25$) then the test data and/or the applied physical model or fitting model may need to be re-evaluated and no more than a constant or a linear function should be used.

FITTING FACTORS FOR UNASSISTED PROJECTILES (MODIFIED POINT MASS MODEL)

3) The Modified Point Mass (MPM) Model uses the following fitting factors for unassisted spin-stabilized projectiles:

Table H.1: Fitting factors for Unassisted Projectiles

Parameter	Symbol	Unit	Typical Limits
Form Factor or Ballistic Coefficient	i C	- lb/in^2	$0.95 < i < 1.05$ no fixed limits
Lift Factor	f_L	-	$0.8 < f_L < 1.2$
Drag Factor	f_D	-	$0.8 < f_D < 1.2$
Yaw Drag Factor	Q_D	-	$0.5 < Q_D < 1.5$
Magnus Force Factor	Q_M	-	$0.5 < Q_M < 1.5$

4) The Form Factor (or Ballistic Coefficient) and Lift Factor are the preferred range and deflection fitting factors. For each charge a maximum 3rd degree polynomial function of quadrant elevation should be fitted through computed i and f_L values from the firing test. Form Factor values may be computed by either iteration towards observed impact points or from measured drag as a function of quadrant elevation. Using the Form Factor implies that the Drag Factor is set to one.

5) The Ballistic Coefficient (C) has become obsolete and should be converted to the Form Factor for use in NATO Fire Control Systems. Second or third degree ballistic coefficients are to be converted by least square approximation; constant and linear ballistic coefficients may be converted by the following equations:

A constant ballistic coefficient may be converted to form factor by:

$$i = \frac{m}{d^2} \cdot \frac{1}{C}$$

A linear ballistic coefficient ($C = C_0 + C_1 \cdot QE$) may be converted to a quadratic form factor function ($i = i_0 + i_1 \cdot QE + i_2 \cdot QE^2$) by:

$$i_k = (-1)^k \frac{m}{d^2} \cdot \frac{C_1^k}{C_0^{k+1}} \text{ (with k = 0 to 2)}$$

6) The Drag Factor (f_D) may be used as an alternative for the Form Factor. Using the Drag Factor implies that the Form Factor is set to one (i=1) and both the Drag Factor and the Lift Factor are 4th degree polynomial functions of Mach number, independent of charge.

7) The Yaw Drag Factor and Magnus Force Factor are optional constants for all charges. If used, the Yaw Drag Factor is commonly set to 1.2, but has typical values between 0.5 and 1.5. The Magnus Force Factor is commonly set to 1.0 in NATO Fire Control Systems, but has typical values between 0.5 and 1.5. These terms are used in the modified point mass model to account for the under prediction of the average projectile yaw, primarily near the summit of the trajectory, for high angle fire.

FITTING FACTORS FOR SPIN-STABILIZED ASSISTED PROJECTILES (MPM MODEL)

8) There are two methods defined in STANAG 4355 for both base-burn and rocket-assisted projectiles. To compensate for the approximations in the additional terms for assisted projectiles certain fitting factors are applied in order to create correspondence between the computed and observed range testing results. These fitting factors are given below.

Table H.2 Fitting Factors for Rocket Assisted Projectiles, Method 1.

Parameter	Symbol	Unit	Typical Limits
Thrust factor	T_f	-	-
Time of rocket motor ignition delay	t_{DI}	s	-
Motor burn time	$t_B - t_{DI}$	s	-
Form factor	i	-	$0.95 < i < 1.05$

Table H.3 Fitting Factors for Base-Burn Projectiles, Method 1.

Parameter	Symbol	Unit	Typical Limits
Time of base-burn motor ignition delay	t_{DI}	s	-
Axial spin burning rate factor	$K(p)$	-	-
Base-burn factor	$f(i_{BB,MT})$	-	-

Table H.4 Fitting Factors for Rocket Assisted Projectiles, Method 2.

Parameter	Symbol	Unit	Typical Limits
Thrust factor	f_t	-	$0.95 < f_t < 1.05$
Exit area of jet	A_e	m^2	1.5 – 3.0
Motor spin rate (p) burning-time factor	f_{BT_p} [1]	-	$-0.5 < f_{BT_p} < -0.1$
Form factor	i	-	$0.95 < i < 1.05$

[1] Optional

Table H.5 Fitting Factors for Base-Burn Projectiles, Method 2.

Parameter	Symbol	Unit	Typical Limits
Base-burn motor spin rate (p) burning-time factor	f_{BT_p}	-	$-0.5 < f_{BT_p} < -0.1$
Base-burn motor atmospheric air pressure (P) burning-time factor	f_{BT_P}	-	$-0.9 < f_{BT_P} < -0.5$
Base-burn factor	$f(i_{BB,MT})$	-	$0.9 < f(i_{BB,MT}) <$ 1.1

9) For base-burn projectiles in method 1, K(p) is a constant to be determined for each charge from experiments to take into account the influence of axial spin on the combustion rate. For base-burn projectiles in method 2 f_{BT_p} and f_{BT_P} are to be determined as constants for each charge to take into account the influence of axial spin and the atmospheric air pressure on the burning time.

10) The factor , $f(i_{BB,MT})$, for base-burn projectiles are to be determined as a function of quadrant elevation (mils), QE, and motor temperature (°C), MT, for each charge as follows:

$$i_{BB\,(MT=21)} = a_0 + a_1 \cdot QE + a_2 \cdot QE^2 + a_3 \cdot QE^3$$

and

$$f(i_{BB,MT}) = i_{BB\,(MT=21)} + b_1\,(MT - 21) + b_2\,(MT - 21)^2 + b_3\,(MT - 21)^3$$

11) Time of rocket or base-burn motor ignition delay (t_{DI}) should be determined as a function of motor temperature (°C) for each charge:

$$t_{DI} = (t_{DI_{ST}})_{(MT=21)} + a_1 \cdot (MT - 21) + a_2 \cdot (MT - 21)^2 + a_3 \cdot (MT - 21)^3$$

12) Time of rocket motor burn (t_B - t_{DI}) should be determined as a function of motor temperature (°C) for each charge:

$$t_B - t_{DI} = (t_{B_{ST}} - t_{DI_{ST}})_{(MT=21)} + a_1 \cdot (MT - 21) + a_2 \cdot (MT - 21)^2 + a_3 \cdot (MT - 21)^3$$

13) Thrust factor (T_f or f_T) should be determined as a function of motor temperature (°C) for each charge:

$$T_f = T_{f\ (MT=21)} + a_1 \cdot (MT - 21) + a_2 \cdot (MT - 21)^2 + a_3 \cdot (MT - 21)^3$$

or

$$f_t = f_{t\ (MT=21)} + a_1 \cdot (MT - 21) + a_2 \cdot (MT - 21)^2 + a_3 \cdot (MT - 21)^3$$

FITTING FACTORS FOR POINT MASS TRAJECTORIES

14) Fire control systems commonly use point mass trajectories for fin-stabilized rounds (most mortars and tank fired munitions), submunitions and for some spin-stabilized rounds; only range-fitting applies. For primary trajectories either a form factor "*i*", ballistic coefficient "C" or drag factor may be used (see paragraphs 3 to 6). For submunitions the submunition form factor "i_{sn}" is to be used.

CORRECTION FACTORS

15) Time of Flight Correction. It may be required to correct the computed time of flight to those values determined during the firing test. If so, a polynomial of no higher than a third degree may be used. However, for use in the MPM model the zero term must be and the second and third order terms are recommended to be zeroed out ($a_0 = 0$).

16) Drift correction. Only applies to the PM model. One of the following functions may be chosen to fit through observed fall of shot results. Other functions may be used but might not be supported by the NATO Armament Ballistic Kernel software. The drift correction should be determined for each applicable charge.

$$Drift = \tan(QE) \cdot (a_0 + a_1 \cdot (QE) + a_2 \cdot (QE)^2 + a_3 \cdot (QE)^3)$$

or

$$Drift = a_0 \tan(QE) + a_1 \cdot \tan(QE)^2$$

or

$$Drift = a_0 QE / (QE + a_1)$$

or

$$Drift = \arctan((a_0 + a_1 \cdot T + a_2 \cdot T^2 + a_3 \cdot T^3)/x_1)$$

where x_1 is the range (m) to impact along the $\vec{1}$ axis.

or

$$Drift = a_0 + a_1(SE) + a_2(SE) + a_3(SE)$$

where SE = QE – AOS,

in which SE is the super elevation, QE is the quadrant elevation and AOS is the angle of sight between the gun and target.

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ANNEX I ROUND TO ROUND PROBABLE ERRORS

INTRODUCTION

1) The probable error indicates the interval at which an event is just as likely to happen as not. In ballistics, round-to-round (precision) probable errors are used to represent the dispersion of the points of impact around a mean point of impact (or the points of air burst around a mean point of air burst) within a single occasion. An occasion represents a series of rounds fired under apparently the same firing conditions (e.g. muzzle velocity, gun, meteo and time frame) and apparently the same aiming elements (e.g. quadrant elevation, azimuth and fuze setting). The dispersion is due to random variations in meteorological and ballistic firing conditions and random changes in aiming elements. These probable errors are a function of the weapon-projectile-charge combination and the quadrant elevation or range. The following round-to-round (also known as precision or consistency) probable errors apply to Fire Control Systems. They comprise a subset of the total NATO Armaments Error Budget as described in STANAG 4635.

a) Indirect Fire

i) Probable Error in Range to Impact (PE_R) - A value which, when added to and subtracted from the expected range, will produce an interval, along the line of fire, that should contain 50 percent of the rounds fired. Variations in muzzle velocity, in angles of departure (elevation and azimuth), and in total drag and lift during flight all contribute to the probable error in range to impact. For those projectiles that are fired with rocket assist, variations in time to the delayed ignition and in thrust performance of the rocket motor are combined with those parameters mentioned above to produce the probable error in range.

ii) Probable Error in Deflection at Impact (PE_D) - A value which, when added both to the right and to the left of the expected impact point, will produce an interval, perpendicular to the line of fire at the expected range, that should contain 50 percent of the rounds fired. Those factors that produce the dispersion in range to impact also produce the dispersion in deflection at impact.

iii) Probable Error in Range to Burst (PE_{RB}) - A value which, when added to and subtracted from the expected range to burst, will produce an interval, along the line of fire, that should contain 50 percent of the rounds fired. The factors that contribute to the probable error in range to burst are not only those that produce dispersion in range to impact, but also those factors attributed to variations in the functioning of the time fuze.

iv) Probable Error in Height of Burst (PE_{HB}) - A value which, when added to and subtracted from the expected height of burst, will produce a vertical interval that should contain 50 percent of the rounds fired. The factors that contribute to the probable error in height of burst are not only those that produce dispersion in range to impact, but also those factors attributed to variations in the functioning of the time fuze.

b) Direct Fire – Vertical Target

v) <u>Probable Error in Height of Impact</u> (PE_H) - A value which, when added to or subtracted from the expected height of impact on a vertical target, will produce a vertical interval that should contain 50 percent of the rounds fired. Variations in muzzle velocity, in angles of departure (elevation and azimuth), and in total drag and lift during flight all contribute to the probable error in the vertical plane. For those projectiles that have a tracer, variations in time to the delayed ignition and in the combustion performance of the tracer are expressed as variations of total drag and lift during flight.

vi) <u>Probable Error in Deflection at Impact</u> (PE_D) - A value which, when added both to the right and to the left of the expected impact point on a vertical target, will produce an interval, perpendicular to the vertical plane of fire at the expected range, that should contain 50 percent of the rounds fired. Those factors that produce the dispersion in height of impact also produce the dispersion in deflection at impact.

2) Dispersion of the points of impact around a mean point of impact (or the points of air burst around a mean point of air burst) within a single occasion may also be represented using standard deviation, as defined in STANAG 4635. Standard deviations in a single direction (range, deflection, or height) can be multiplied by 0.6745 to convert to probable errors.

3) There are two ways that Fire Control Systems may use to calculate the numerical values for the probable errors. First there is the Polynomial Compensation Approach, where the probable errors are given as a function of quadrant elevation or range. Next there is the Error Budget Approach, where the different parameters contributing to the probable errors are separately accounted for. Both ways take into account the results of live firings (see Annex B).

THE POLYNOMIAL COMPENSATION APPROACH

4) Probable errors in the polynomial compensation approach are given as a function of quadrant elevation or range for a mean occasion at near standard firing conditions (e.g. weapon and target height near sea level). The polynomial functions may be determined from the error budget approach; the opposite is not true. Alternatively, the polynomial functions are determined from a direct fit to measured values of the probable errors. The latter can be measured values of the probable errors or a set of trajectory measurements (if Doppler/Tracking Radar data is available). The advantage of this approach is its simplicity, as it does not require the use of trajectory computations in the calculation the probable errors; thus can also be used by other than Fire Control Systems (e.g. for safety and hazard analysis). The following equations using Quadrant Elevation (QE), in mils, and/or Range (R), in meters, are to be used for:

a) Indirect Fire

i) Probable Error in Range to Impact (PE_R), Range to Burst (PE_{RB}) and Height of Burst (PE_{HB})

$$PE_R = a_0 + a_1 QE + a_2 QE^2 + a_3 QE^3$$
$$PE_{RB} = a_0 + a_1 QE + a_2 QE^2 + a_3 QE^3$$
$$PE_{HB} = a_0 + a_1 QE + a_2 QE^2 + a_3 QE^3$$

ii) Probable Error in Deflection at Impact (PE_D); optionally defined as a set of functions between QE validity limits

$$PE_D = R * \left(a_1 * \frac{2\pi}{6400} * \frac{a_2}{a_2 - QE} + \frac{b_1}{\cos(QE)} \right)$$

where b must be larger than 1600 mils and usually is rounded to the nearest hundred.

b) Direct Fire – Vertical Target

i) Probable Error in Height of Impact (PE_H)

$$PE_H = a_0 + a_1 R + a_2 R^2 + a_3 R^3$$

ii) Probable Error in Deflection at Impact (PE_D)

$$PE_D = a_0 + a_1 R + a_2 R^2 + a_3 R^3$$

The coefficients for the polynomial functions are to be fitted from either:

I. Calculated values using the Error Budget Approach (preferred method). The Polynomial Compensation Approach may use the Error Budget Approach, the opposite is not true.

II. Measured values of a set of trajectory measurements (drag and time to burst). The probable error in range to impact as a function of quadrant elevation may be calculated from the probable error in drag (C_D) or ballistic form factor (i) as function of Mach. For this the calculated range differences for trajectories using mean drag plus or minus probable error in drag are used. Next, including the probable error in time to burst gives the probable error in range to burst and height of burst. The advantage of this method over fitting impact data is the combination of trajectory data from all occasions, quadrant elevations and muzzle velocities.

III. Measured values of the probable errors to impact. Fitting the functions for probable error in range, deflection and/or height to impact directly from impact data needs a larger number of occasions per charge to obtain reliable and reproducible results. Preferably, probable error functions obtained in this manner are presented in the Test Data Summary (Annex J).

THE ERROR BUDGET APPROACH

5) The probable errors in the error budget approach are composed from individual error budget components. Each component is to be quantified from real firing measurements. The advantage of the error budget approach is that it can be used in a field computer to determine probable errors for the actual (real-time) firing conditions.

6) The following probable error components are taken into account: muzzle velocity (PE_{MV}), projectile mass (PE_m), ballistic form factor (PE_i), lift factor (PE_{f_L}) quadrant elevation (PE_{QE}), azimuth (PE_{AZ}), time of motor ignition delay ($PE_{t_{DI}}$), base burn factor ($PE_{f_{BB}}$) and thrust factor (PE_{T_f}). If analysis proves that an error budget term is negligible then it may be omitted; likewise if an additional term is considered necessary it may be included.

a) Indirect Fire

$$PE_R^2 = PE_{MV}^2\left(\frac{\partial R}{\partial v_0}\right)_h^2 + PE_m^2\left(\frac{\partial R}{\partial m} + \frac{\partial R}{\partial v_0}\frac{\partial v_0}{\partial m}\right)_h^2 + PE_i^2\left(\frac{\partial R}{\partial i}\right)_h^2 + PE_{QE}^2\left(\frac{\partial R}{\partial QE}\right)_h^2 +$$

$$PE_{t_{DI}}^2\left(\frac{\partial R}{\partial t_{DI}}\right)_h^2 + PE_{f_{BB}}^2\left(\frac{\partial R}{\partial f_{BB}}\right)_h^2 + PE_{T_f}^2\left(\frac{\partial R}{\partial T_f}\right)_h^2$$

$$PE_D^2 = PE_{f_L}^2\left(\frac{\partial D}{\partial f_L}\right)_h^2 + PE_{AZ}^2\left(\frac{\partial D}{\partial AZ}\right)_h^2$$

$$PE_{RB}^2 = PE_{MV}^2\left(\frac{\partial R}{\partial v_0}\right)_t^2 + PE_m^2\left(\frac{\partial R}{\partial m} + \frac{\partial R}{\partial v_0}\frac{\partial v_0}{\partial m}\right)_h^2 + PE_i^2\left(\frac{\partial R}{\partial i}\right)_t^2 + PE_{QE}^2\left(\frac{\partial R}{\partial QE}\right)_t^2 +$$

$$PE_{t_{DI}}^2\left(\frac{\partial R}{\partial t_{DI}}\right)_t^2 + PE_{f_{BB}}^2\left(\frac{\partial R}{\partial f_{BB}}\right)_t^2 + PE_{T_f}^2\left(\frac{\partial R}{\partial T_f}\right)_t^2 + PE_{FT}^2\left(\frac{\partial R}{\partial FT}\right)_t^2$$

$$PE_{HB}^2 = PE_{MV}^2\left(\frac{\partial h}{\partial v_0}\right)_t^2 + PE_m^2\left(\frac{\partial h}{\partial m} + \frac{\partial h}{\partial v_0}\frac{\partial v_0}{\partial m}\right)_t^2 + PE_i^2\left(\frac{\partial h}{\partial i}\right)_t^2 + PE_{QE}^2\left(\frac{\partial h}{\partial QE}\right)_t^2 +$$

$$PE_{t_{DI}}^2\left(\frac{\partial h}{\partial t_{DI}}\right)_t^2 + PE_{f_{BB}}^2\left(\frac{\partial h}{\partial f_{BB}}\right)_t^2 + PE_{T_f}^2\left(\frac{\partial h}{\partial T_f}\right)_t^2 + PE_{FT}^2\left(\frac{\partial h}{\partial FT}\right)_t^2$$

b) Direct Fire – Vertical Target

$$PE_H^2 = PE_{MV}^2\left(\frac{\partial H}{\partial v_0}\right)_r^2 + PE_m^2\left(\frac{\partial H}{\partial m} + \frac{\partial H}{\partial v_0}\frac{\partial v_0}{\partial m}\right)_r^2 + PE_i^2\left(\frac{\partial H}{\partial i}\right)_r^2 + PE_{QE}^2\left(\frac{\partial H}{\partial QE}\right)_r^2 +$$

$$PE_{t_{DI}}^2\left(\frac{\partial H}{\partial t_{DI}}\right)_r^2 + PE_{f_{BB}}^2\left(\frac{\partial H}{\partial f_{BB}}\right)_r^2 + PE_{T_f}^2\left(\frac{\partial H}{\partial T_f}\right)_r^2$$

$$PE_D^2 = PE_{MV}^2\left(\frac{\partial D}{\partial v_0}\right)_r^2 + PE_m^2\left(\frac{\partial D}{\partial m} + \frac{\partial D}{\partial v_0}\frac{\partial v_0}{\partial m}\right)_r^2 + PE_i^2\left(\frac{\partial D}{\partial i}\right)_r^2 + PE_{QE}^2\left(\frac{\partial D}{\partial QE}\right)_r^2 +$$

$$PE_{f_L}^2\left(\frac{\partial D}{\partial f_L}\right)_r^2 + PE_{AZ}^2\left(\frac{\partial D}{\partial AZ}\right)_r^2 + PE_{t_{DI}}^2\left(\frac{\partial D}{\partial t_{DI}}\right)_r^2 + PE_{f_{BB}}^2\left(\frac{\partial D}{\partial f_{BB}}\right)_r^2 + PE_{T_f}^2\left(\frac{\partial D}{\partial T_f}\right)_r^2$$

$PE_{f_{BB}}$ only applies to base burn projectiles, PE_{T_f} only applies to rocket assisted projectiles and $PE_{t_{DI}}$ applies to both base burn and rocket assisted projectiles.

7) The probable error components are to be determined by national procedures in accordance with Annex C.

I. The probable error in projectile mass (PE_m) must be a constant.

II. The probable error in muzzle velocity (PE_{MV}) is to be determined as a constant per charge for the weapon system.

III. The probable errors in quadrant elevation (PE_{QE}) and firing azimuth (PE_{AZ}) are generally constant but may be determined as constant per charge for the weapon system. These terms may include the error components from multiple sources that affect the true pointing of the initial velocity vector during the firing event such as projectile jump, barrel whip, ship/deck flexure (for naval indirect fire systems), etc.

IV. Probable errors in form factor (PE_i) and lift factor (PE_{f_L}) are to be determined for each charge. They are generally constant per charge but may be a function of quadrant elevation of maximum third degree. These terms may include the error components from multiple sources that affect the net forces on the projectile during its flight such as initial yaw rate, projectile surface finish, projectile engraving, tracer burn time, etc.

$$PE_i = a_0 + a_1 QE + a_2 QE^2 + a_3 QE^3$$
$$PE_{f_L} = a_0 + a_1 QE + a_2 QE^2 + a_3 QE^3$$

V. Probable error in fuze time (PE_{FT}) is to be determined as function of time of flight.

$$PE_{FT} = a_0 + a_1 TOF + a_2 TOF^2 + a_3 TOF^3$$

<u>FORK (artillery only)</u>

8) Fire Control Computers may need fork to check for crest violations. Fork is defined as the change in angle of elevation necessary to produce a change in range at the level point equivalent to four probable errors in range to impact at standard firing conditions; this is to be calculated from the probable error in range to impact. It may be given as a set of functions for successive quadrant elevation limits from minimum to maximum system quadrant elevation. The following general equation may be used for any of these function intervals:

$$FORK = \frac{a_0 \cdot QE + a_1 \cdot QE^2}{QE - a_4} + a_2 \cdot QE^2 + a_3 \cdot QE^3$$

Generally, either a_4 (France) or a_2 and a_3 (US) are zeroed out. The fork function must fit within 0.1 mil of the values calculated by the trajectory model at any valid quadrant elevation.

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ANNEX J TEST DATA SUMMARY

1) The Test Data Summary is a tabular and/or graphical representation of statistical mean and variation of Fire Control Data. Fire Control Inputs to be exchanged from one NATO country to another are to be accompanied by a Test Data summary.

a) The Test Data Summary must contain:

i) Firing Test Plan made.
ii) Measurements available.
iii) Guide lines of the process used to establish the set of ballistic data.

And a statistical report giving:

iv) For Artillery, Mortars and Naval Guns (Indirect Fire):

(1) Observed fitting factors versus independent variable (QE, time, temperature, Mach number) per charge. Examples are given in Figures J.1 to J.4.

(2) Range, drift and time of flight residuals at impact point versus muzzle velocity or charge at equal quadrant elevation. An example is shown in Figure J.5.

or

Range, height and deflection residuals along the trajectory or at impact for each firing. Examples are given in Figures J.6, J.7, and J.8.

(3) Probable errors, for each component used in the Error Budget Approach (Annex I) the sample size and 95 % uncertainty limits should be given.

Table J.1: Probable error components for the error budget.

Component[a]	Symbol	Unit
Probable Error in Projectile Mass	PE_m	kg
Probable Error in Muzzle Velocity	PE_{MV}	m/s
Probable Error in Quadrant Elevation	PE_{QE}	mils
Probable Error in Firing Azimuth	PE_{AZ}	mils
Probable Error in Form Factor	PE_i	-
Probable Error in Lift Factor	PE_{f_L}	-
Probable Error in Fuze Time	PE_{FT}	s

Probable Error in Ignition Delay Time	$PE_{t_{DI}}$	s
Probable Error in Base-burn Factor	$PE_{f_{BB}}$	%
Probable Error in Thrust Factor	PE_{T_f}	%

(a) These components represent only the round-to-round probable errors that form a subset of the total error budget as defined in STANAG 4635.

(4) For base-burn projectiles:

(a) Experimental Doppler measurement reduced in terms of drag coefficient versus standard drag during base-burn phase (STANAG 4355, Base Burn Method 1). An example is shown in Figure J.9.

(b) Base-burn factor versus quadrant elevation (STANAG 4355, Base Burn Method 2). An example is shown in Figure J.10.

(c) Measured base-burn time versus standard base-burn time.

v) For Direct Fire:

(1) Observed fitting factors versus independent variable (QE, time, temperature, range).

(2) Vertical, horizontal, and, if appropriate, time of flight residuals at vertical target impact point versus range.

b) Desirably the Test Data Summary further contains:

i) A statistical summary of physical data.
ii) Total drag (C_D) versus Mach. An example is shown in Figure J.11.
iii) A statistical summary of other fitted quadrant elevation, range, time, temperature, and Mach dependent functions.
iv) An internal ballistic data report.

2) The presentation of fitted polynomial functions should contain all values used in the fit along with the polynomial coefficients and the correlation coefficient (R^2). Typical limits for the absolute value of the correlation coefficient are: 0.00-0.20 no correlation, 0.20-0.40 poor correlation, 0.40-0.80 moderate to good correlation, 0.80-1.00 very good correlation. Polynomial functions with no or poor correlation to the experimental values may require additional analysis.

3) Internal ballistic inputs for the simulation model defined in STANAG 4367 are needed to perform the simulations referenced in Annex F. Creation of validated inputs requires certain ballistic data that are not part of Fire Control Inputs. For this reason it is recommended to add internal ballistic data and/or input files for the IBHVG2 code for all charges to the Test Data Summary. The following data is identified: maximum pressure, breech pressure versus time and preferably, in-bore projectile velocity, resistance profile, friction coefficient, heat transfer to gun barrel and barrel recoil distance.

4) Example Figures.

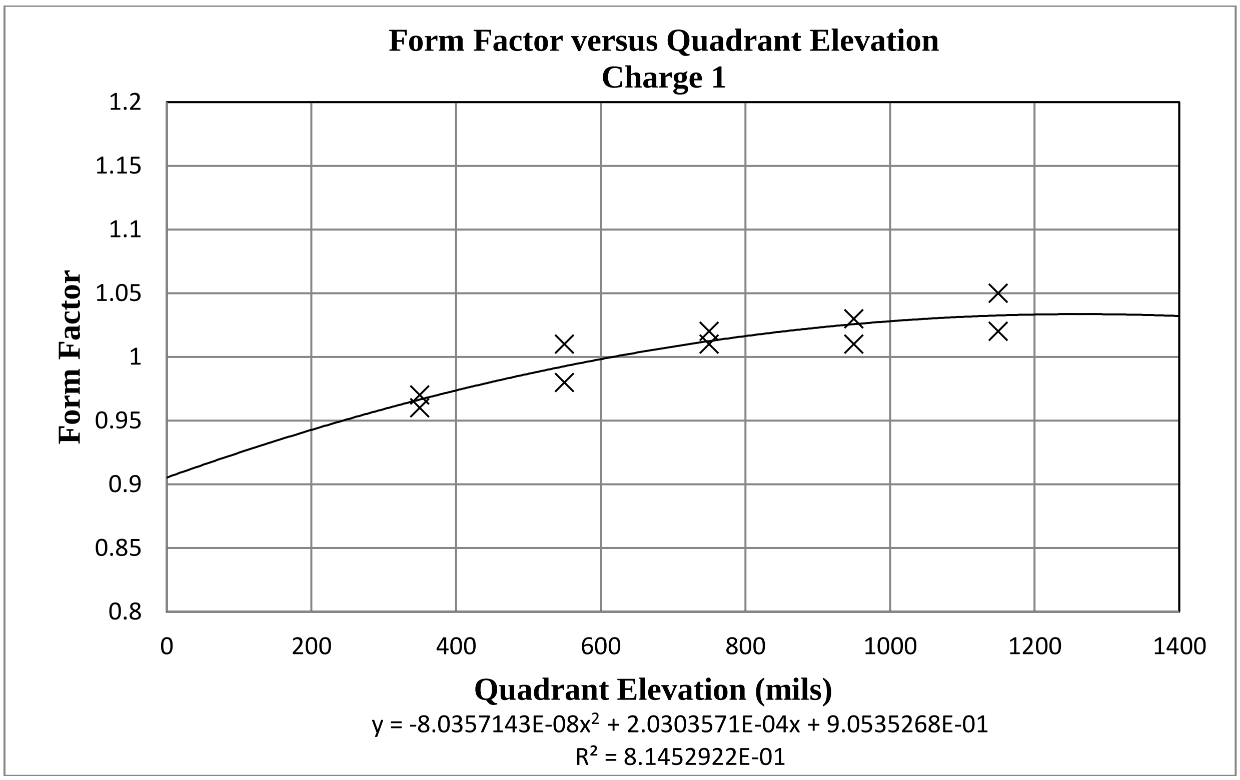

Figure J.1. Form Factor versus Quadrant Elevation.

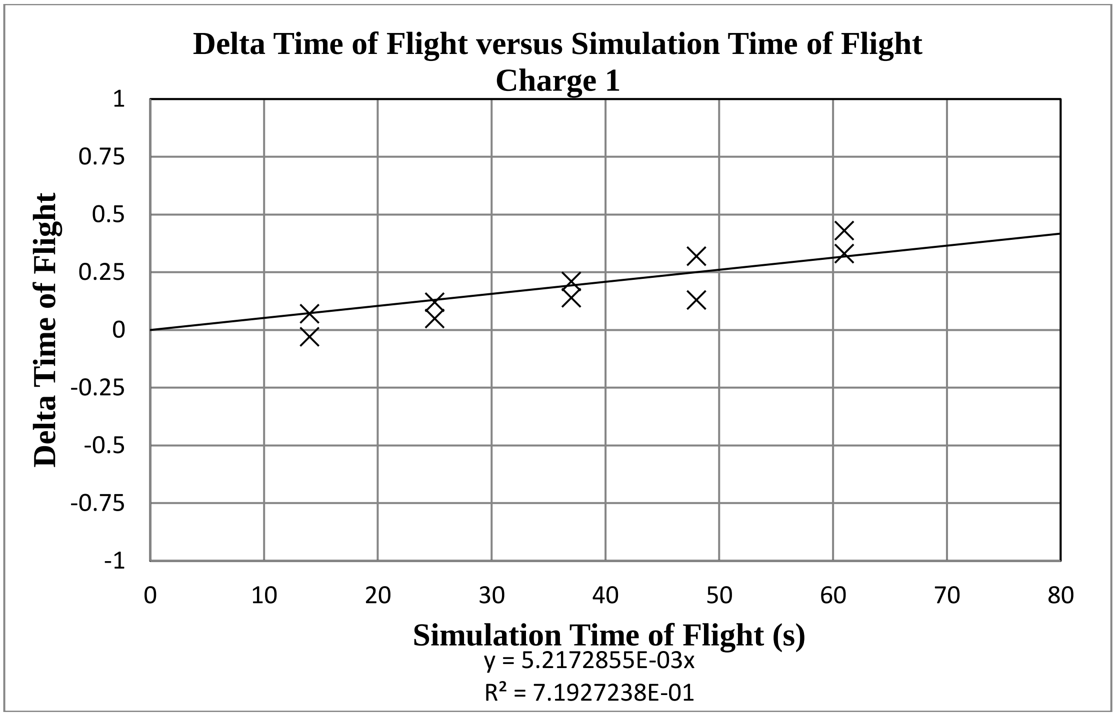

Figure J.2. Delta Time of Flight versus Simulation Time of Flight.

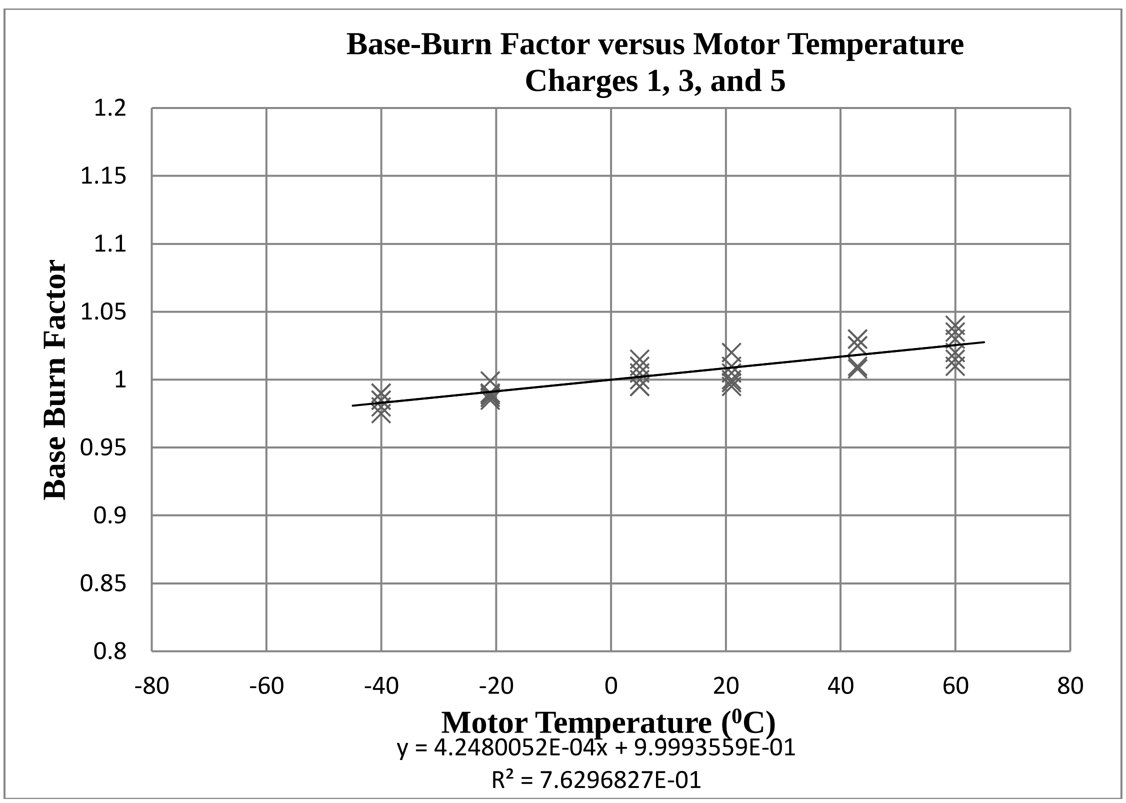

Figure J.3: Firing Data Base-Burn Factor versus Motor Temperature.

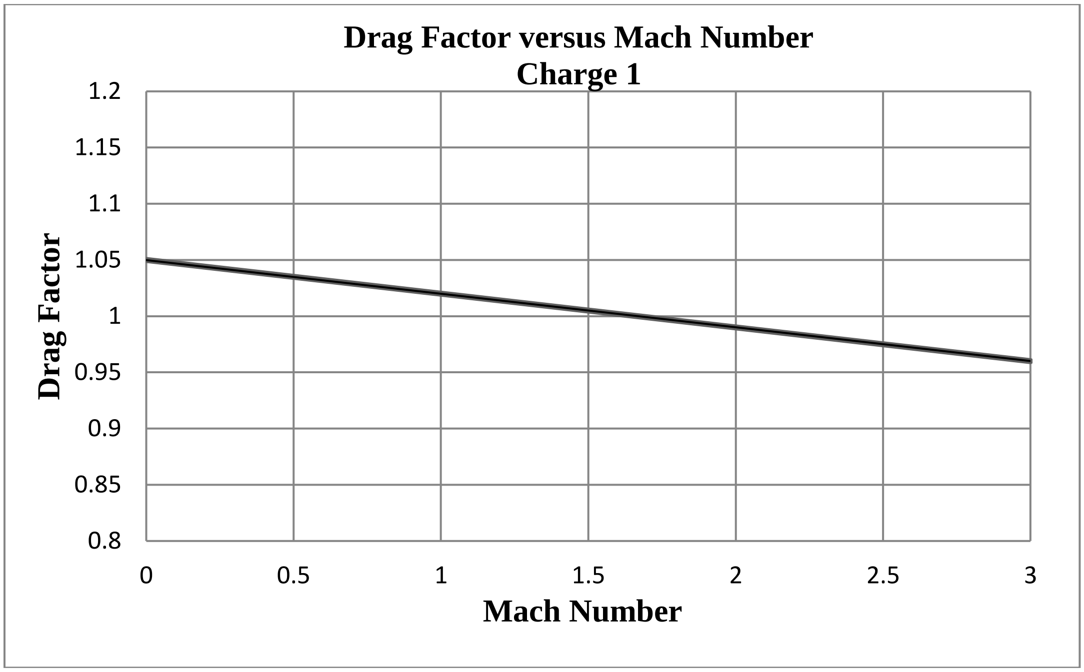

Figure J.4: Drag Factor versus Mach Number.

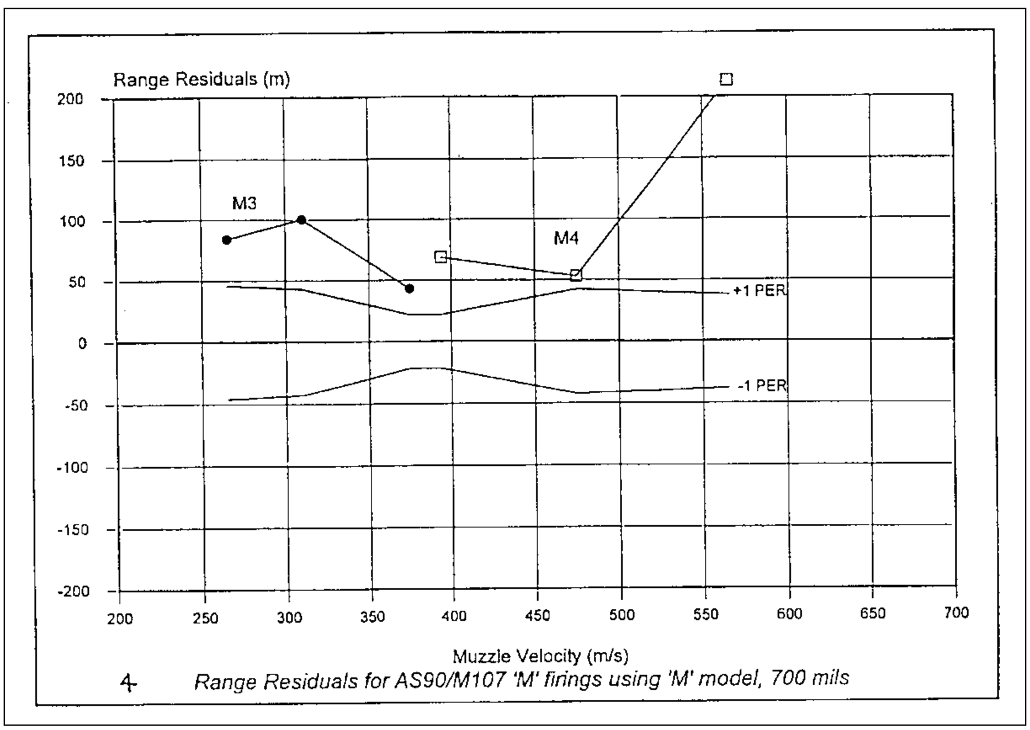

Figure J.5: Range Residuals versus Muzzle Velocity at Equal Quadrant Elevation

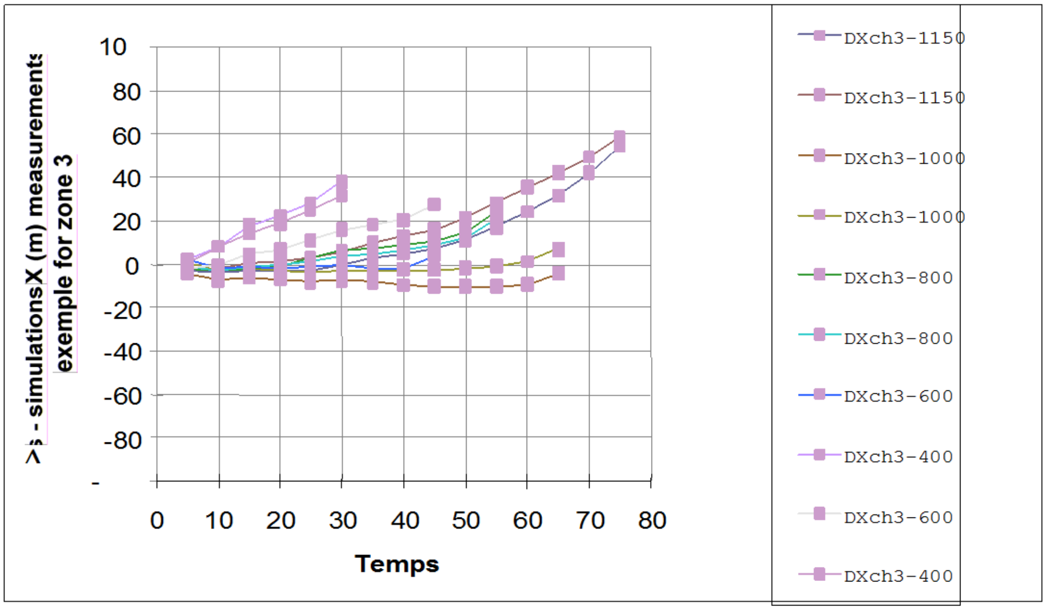

Figure J.6: Range Differences versus Measured Time at 10 Quadrant Elevations.

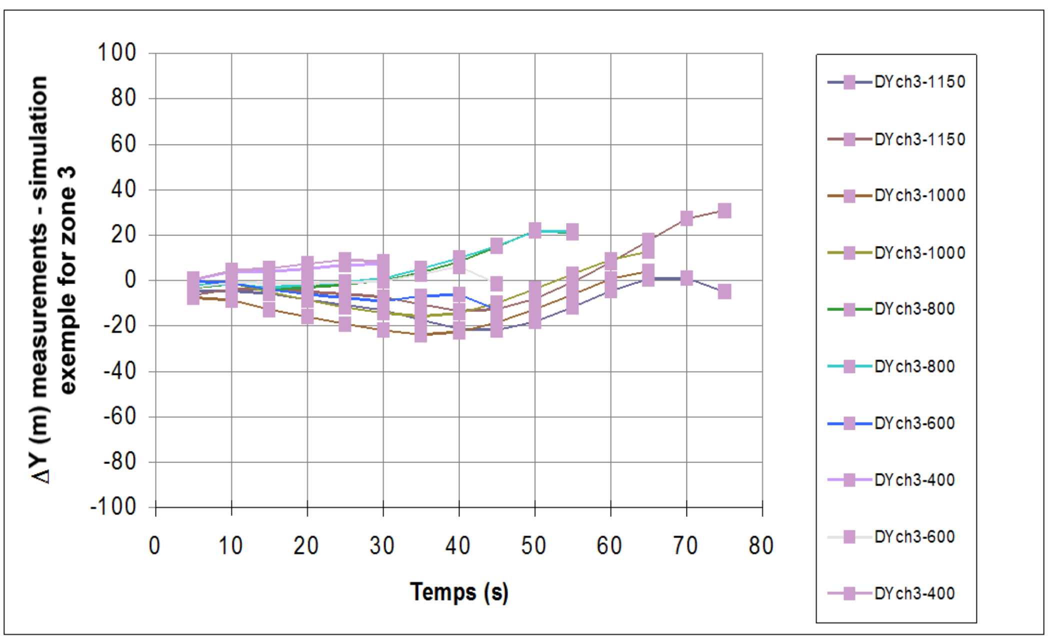

Figure J.7: Height Differences versus Measured Time at 10 Quadrant Elevations.

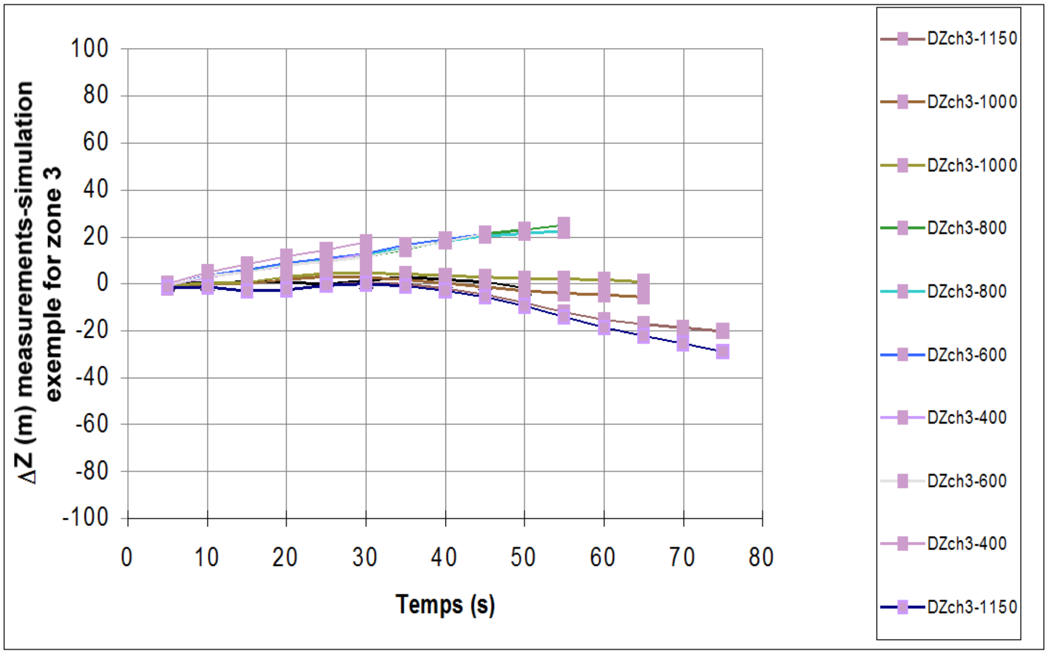

Figure J.8: Deflection Differences (m) versus Measured Time at 10 Quadrant Elevations.

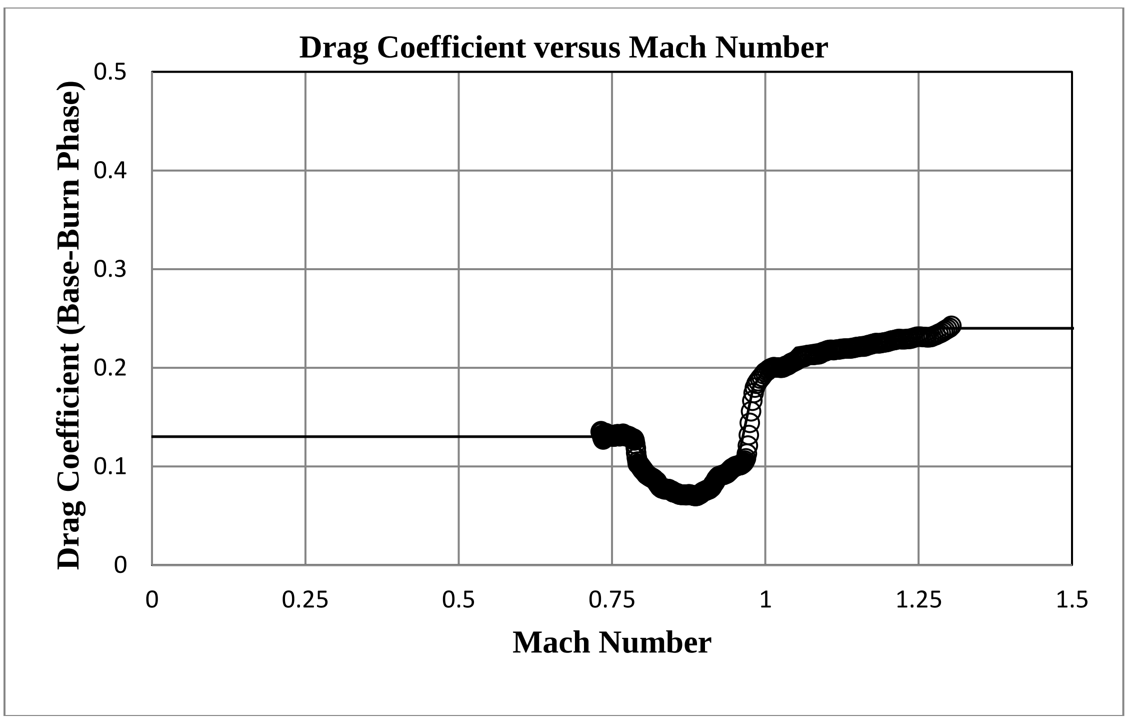

Figure J.9: Measured Drag Coefficient versus Mach Number for base-burn projectile during burn phase

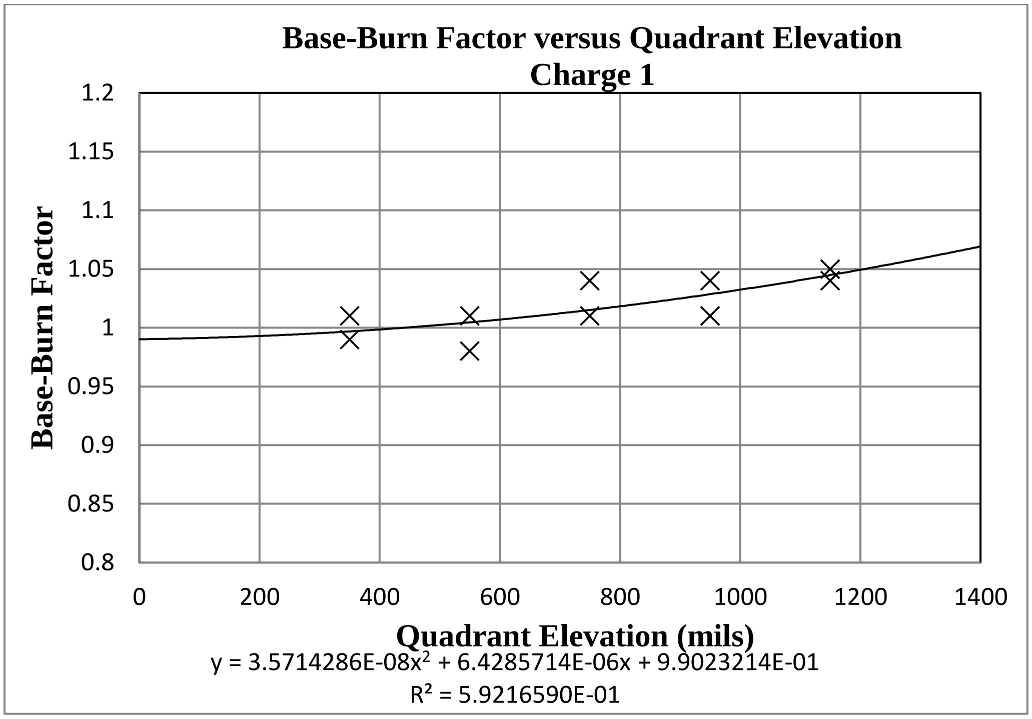

Figure J.10: Base-Burn Factor versus Quadrant Elevation for base-burn projectile

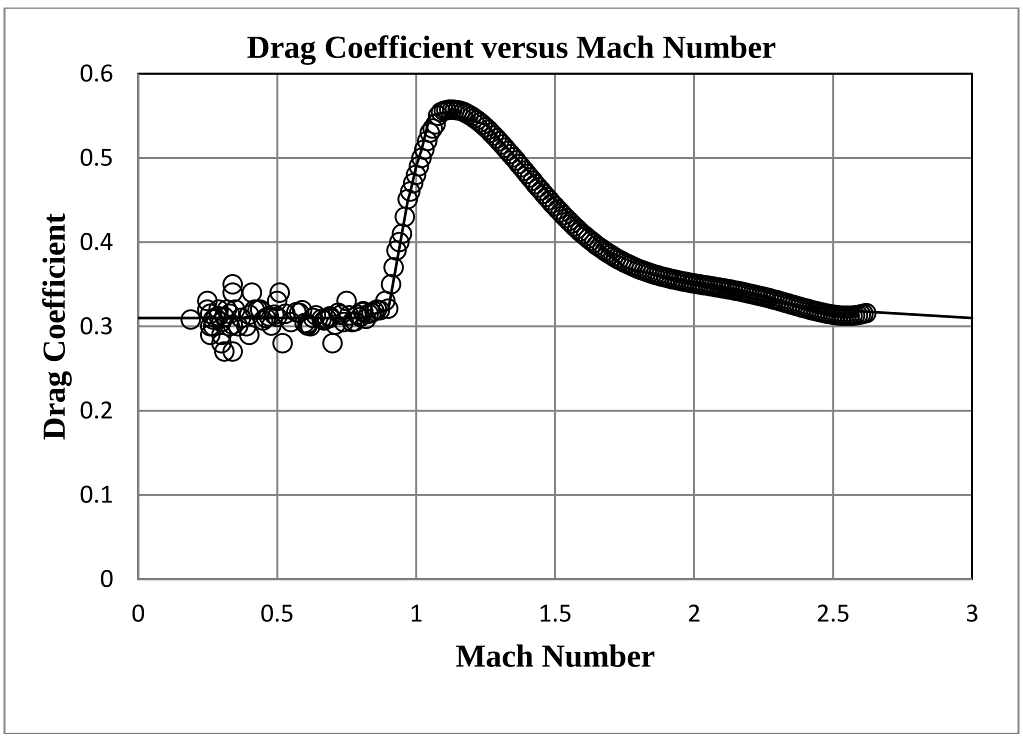

Figure J.11: Measured Drag Coefficient (Total) versus Mach Number

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AOP-65(A)(1)