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Doctoral Dissertation

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Helsinki University of Technology
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Abstract
The dissertation was intended to improve the quality and safety of gun propelling charges during their life cycle. The approach in three case studies was the evaluation of gun propelling charge performance by the statistical utilization of the results collected in artillery gun test firings and conscript practice troop firings.

The interior ballistics branch needs to adjust to the new demands for weapon systems. The literature review shows that the actual interdisciplinary challenges entail the development of new, more energetic but less sensitive and toxic gun propellant compositions, the development of high loading density charge constructions, enhancing the knowledge about the ignition event, research on heat transfer in the gun barrel and barrel wear and further development of mathematical modeling.

Primarily due to firing safety it is essential to be able to measure correct pressure values during the ignition and combustion of gun propelling charges in test firings. A discrepancy was detected in the maximum pressure levels measured by using two different pressure measurement methods in the interior ballistic test firings. This problem has been resolved by the development of a new dynamic calibration methodology for the crusher gauge pressure elements. The calibration methodology developed was verified and implemented (Case I).

The acceptance control must provide a reliable baseline for the assessment of the performance of gun propelling charges. Quality defects were found in several recently produced 155-mm gun propelling charge lots. The reasons for the poor performance of the procedure for determining gun propelling charge weight were ascertained by applying multivariate analysis methods in new ways to the data set consisting of 155 mm charge weight establishment and uniformity test firing results (Case II). It was found possible to improve the test procedure.

The chemical and physical changes occurring during the life cycle of gun propelling charges may impair their safety and performance. It is essential to be aware of such changes as early as possible in the life cycle of the gun propelling charge type. Thanks to new technology, the acquisition of information on ammunition performance is no longer limited to the test firings. The new surveillance system developed and implemented enables the utilization of conscript practice field artillery troop firings for performance data collection of gun propelling charges (Case III).

Keywords Interior ballistics, gun propelling charges, test firings, practice troop firings, multivariate analysis

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Tiivistelmä

Tässä tutkimuksessa on kehitetty uusia menetelmiä aseruutipanosten laadun ja turvallisuuden parantamiseksi niiden elinjakson aikana. Menetelmänä kolmen tutkimustapauksen tarkastelussa oli tykistön koe- tai koulutusammunnoissa kerättyjen tietojen tilastollinen käsittely.

Sisäballistiikan tutkimusalan tulee mukautua asejärjestelmille asetettuihin uusiin vaateisiin. Kirjallisuusselvityksen perusteella alan ajankohtaisiin poikkitieteellisiin haasteisiin lukeutuvat uusien, entistä energisempien, mutta toisaalta entistä epäherkempien ja myrkyttömämpien, aseruutikoostumusten kehittäminen, lataustiheydeltään entistä suurempien aseruutipanosten suunnittelu, perusteellisemman tietotaidon hankinta aseruutipanoksen sytytystapahtumasta, aseen putkessa tapahtuvan lämmönsiirron tarkastelu, aseen kulumisen tutkimus sekä sisäballistiikan matemaattisen mallinnuksen jatkuva kehittäminen.

Ensisijaisesti ammuntaturvallisuuden varmistamiseksi on sisäballistisissa koeammunnoissa pystyttävä mittaamaan aseruutipanosten syttymisen ja palamisen aikana panoskammiossa esiintyvät todelliset painearvot. Kahden eri paineenmittausmenetelmän antamissa huippupainearvoissa oli sisäballistisissa koeammunnoissa todettu tasoero. Tämä ongelma on selvitetty kehittämällä uusi crusher-painemittarin dynaaminen kalibrointimenetelmä. Kehitetty kalibrointimenetelmä on verifioitu ja implementoitu (tapaus I).

Vastaanottoammuntojen tulosten tulee antaa luotettava perusta uuden aseruutipanoserän suorituskyvyn lähtöarvojen määrittämiselle. Useissa viime vuosina valmistetuissa 155 mm aseruutipanoserissä oli todettu laatupoikkeamia. Syitä käytetyn panosmääritysprosessin heikkoon suorituskykyyn saatiin selvitettyä soveltamalla monimuuttuja-analyysiä uudella tavalla 155 mm aseruutipanosten panosmääritys- ja vastaanottoammuntojen tuloksista koostuvan aineiston tarkasteluun (tapaus II). Panosmääritysprosessia voitiin parantaa.

Aseruutipanosten turvallisuus ja suorituskyky voivat heikentyä elinjakson aikaisten kemiallisten ja fysikaalisten muutosten vaikutuksesta. On tärkeätä saada tietoa näistä aseruutipanostyyppikohtaisista muutoksista aikaisessa vaiheessa elinjaksoa. Uuden teknologian ansiosta tiedonhankinta laukausten suorituskyvystä ei enää rajoitu koeammuntoihin. Uutta, implementoitua valvontajärjestelmää käyttäen voidaan myös kenttätykistön koulutusammunnoista kerätä aseruutipanosten suorituskykytietoja (tapaus III).

Asiasanat Sisäballistiikka, aseruutipanokset, koeammunnat, joukkojen koulutusammunnat, monimuuttuja-analyysi	
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Preface

The research described in this dissertation was carried out in the Army Materiel Command Headquarters (until the beginning of 2008 Defence Forces Materiel Command) during the period 2004-2008. The part involving the development and verification of the dynamic calibration method for crusher gauges was carried out in co-operation with Tampere University of Technology, Institute of Materials Science.

I am very grateful to my supervisor, Professor Outi Krause for her guidance and encouragement during this work. I also thank my co-authors for their contributions to the publications. I warmly thank my colleagues for co-operation and advice. I thank my employer for giving me the opportunity to carry out this work. I thank Virginia Mattila for revising the language of this dissertation and the publications.

Tampere May 2008

Heli Nyberg

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Nyberg, H., Kuokkala, V.-T., Rämö J., Järviniemi, A., A dynamic calibration method for crusher gauges based on material testing, *Propellants, Explos., Pyrotech.* **31** (2007) 61-67.

II Nyberg, H., Hurme, T., Penttilä, O.-P., Multivariate Analysis Applied to Test Procedure for Determining Gun Propelling Charge Weight Part I. Preliminary Analysis of the Data Set. *Chemom. Intell. Lab. Syst.* **87** (2007) 131-138.

III Nyberg, H., Multivariate analysis applied to a test procedure for determining gun propelling charge weight Part II. Partial least squares regression analysis, *Chemom. Intell. Lab. Syst.*, **92** (2008) 118-124.

IV Nyberg, H. M., Muikku, T. P. O., Conscript practice troop firings utilizing surveillance system for propellant charges, in *Proceedings of the 37th International Annual Conference of ICT*, Karlsruhe, Germany, 27-30 June 2006, V23 1-12.

V Nyberg, H., Evaluation of data collected by a surveillance system for gun propelling charges utilizing conscript practice troop firings, *J. Battlefield Technology* **10** (2007) 13-18.

Author's contribution

I The publication is related to MATINE research project Nr. 616, which was carried out in cooperation between Tampere University of Technology and the Defence Forces Test Firing Centre (Finland). The author continued the work by verifying and implementation of the laboratory model developed during the project. She planned the research and conducted the selection and pre-processing of the test firing data. She also carried out the modeling of the data and interpreted the results. She wrote the manuscript together with the co-authors.

II After the preliminary analysis of part of the data carried out by the co-authors, the author continued the research. She carried out the statistical and the principal component analyses. She interpreted the results and wrote the manuscript.

III The author carried out the research, interpreted the results and wrote the manuscript.

IV The paper is related to the surveillance system for propellant charges development project carried out in the Defence Forces Materiel Command Headquarters (Finland). In the project the author was as a project manager responsible for the planning, development and initial implementation of the surveillance system. She planned and developed the Muzzle Velocity Database and calculation methods together with the co-author. She planned the research, analyzed and interpreted the results and wrote the manuscript.

V The author carried out the research, interpreted the results and wrote the manuscript.

List of Abbreviations

0D	Zero-dimensional
1D	One-dimensional
2D	Two-dimensional
AII	Acardite II
ADN	Ammonium dinitramide
AEP	Allied Engineering Publication (NATO)
AOP	Allied Ordnance Publication (NATO)
ARL	U.S. Army Research Laboratory
BAMO/NMMO	Copolymer of 3,3-bis(Azidomethyl)oxetane and 3-nitratomethyl-3-methyloxetane
BuNENA	Buthylnitratoethylnitramine
CFD	Computational Fluid Dynamics
CL20	Hexanitrohexaazaisowurtzitane
CTA	Cased telescoped ammunition
DBP	Dibutyl phtalate
DEGDN	Diethylene glycol dinitrate
DINA	Dinitroxyethyldiethyl nitramine
DNDA	Dinitro diaza
DNT	Dinitrotoluene
DPA	Diphenylamine
EC	Ethyl centralite
ETC	Electrothermal-chemical
ETI	Thermal-chemical ignition
ETPE	Energetic thermoplastic elastomer
FDF	The Finnish Defence Forces
FEM	Finite element method
FOX 12	N-Guanylureadinitramide, GUDN
GAP	Hydroxy-terminated glycidylazidepolymer
GUDN	N-guanylureadinitramide, FOX 12
IM	Insensitive munitions
ITOP	International Test Operation Procedure
JA2 propellant	NC 59% (13.1% N), NG 15%, DEGDN 25%, AII 1%
LOVA	Low vulnerability ammunition
LTC	Low temperature coefficient
M14 propellant	NC 89% (13% N), DNT 8%, DBP 2%, DPA 1%
M30A1 propellant	NC 27% (12.6% N), NG 23.4%, NQ 47.2%, EC 1.4%, K_2SO_4 1%
M43 propellant	NC 4% (12.6% N), RDX 76%, CAB 12%, plasticizer 8%
MeNENA	Methylnitratoethylnitramine
MSIAC	Munitions Safety Information Analysis Center
MultiD	Multidimensional
NATO	North Atlantic Treaty Organization

NC	Nitrocellulose
NENA	Nitratoethylnitramine
NENA-0	MeNENA 14.85%, NC 49.45%, DINA 34.70% Centralite: 1.0%
NENA-Bu 15	BuNENA 14.85%, NC 49.45%, DINA 34.70%, Centralite 1.0%
NG	Nitroglycerine
NQ	Nitroguanidine
PCA	Principal component analysis
PLS	Partial least squares regression
PolyGLYN	Poly-glycidylnitrate
PolyNIMMO	Poly[3-nitratomethyl-3-methyloxetane]
RDX	Cyclotrimethylenetrinitramine
STANAG	Standardization Agreement (NATO)
TNAZ	3,3-Trinitroazetidine
TPE	Thermoplastic elastomer
V-LAP	Velocity-enhanced long range artillery projectile

1 Introduction

1.1 General

The science of interior ballistics is concerned with the propulsion of a projectile along the tube of a weapon by the gas pressure on the base of the projectile, or, for rockets, by the backward exhaust of the gas jet. The interior ballistic cycle includes all the phenomena taking place during the tube phases of gun firing [1-2]. The kinetic energy transmitted to the projectile in gun systems (to be discussed in this dissertation), or the work to be done against external forces such as the deformation force of the rotating band, is produced by an exothermic and gas producing reaction of solid propellants.

The most important methods to study interior ballistics in the test firings are the muzzle velocity measurement by doppler radar and the pressure measurement from the combustion chamber by pressure gauges. The projectile travel and the pressure in the gun barrel are presented as a function of time or barrel length and provide the frame of reference and basic information about the course of events occurring in the launching of projectiles from guns [3]. One possibility to gain information about the projectile motion in-bore and the muzzle’s vibration angular amplitude is a semi-conductor laser and photoelectrical position sensor measurement [4]. On laboratory scale the most important test equipment is the closed vessel (or ballistic bomb) used in the determination of the burning properties of propellants [5].

The recent developments of propulsion systems and interior ballistics are briefly reviewed in this dissertation. A comprehensive review is beyond the scope of this dissertation and is demanding to produce because much of the information is confidential. It is characteristic for the interior ballistics branch, that most of the research results are published in the proceedings of international conferences instead of peer reviewed journals. The description of the development trends of the projectiles is excluded from this review.

The Finnish Defence Forces (FDF) have outsourced the design and mostly the production of gun propelling charges during the 2000s. This work has included co-operation of the FDF and the Finnish defense industry in the development of the procedures concerning the life cycle of gun propelling charges. In this context the life cycle of the gun propelling charge is determined to begin from concept exploration and design and to end at eventual use or disposal as presented in Figure 1.1 [6]. In the course of this development work several applicable international instructions and NATO standards have been implemented. Some new methodologies have also been implemented. Among them are mathematical modeling of interior ballistics and methods for the prediction and monitoring of the functional life of gun propelling charges. For the FDF it is essential to fully understand the procedures included in the life cycle of gun propelling charges in order to be able to procure, store, maintain, use and dispose the propelling charges in a competitive, cost-effective safe and eco-friendly way.

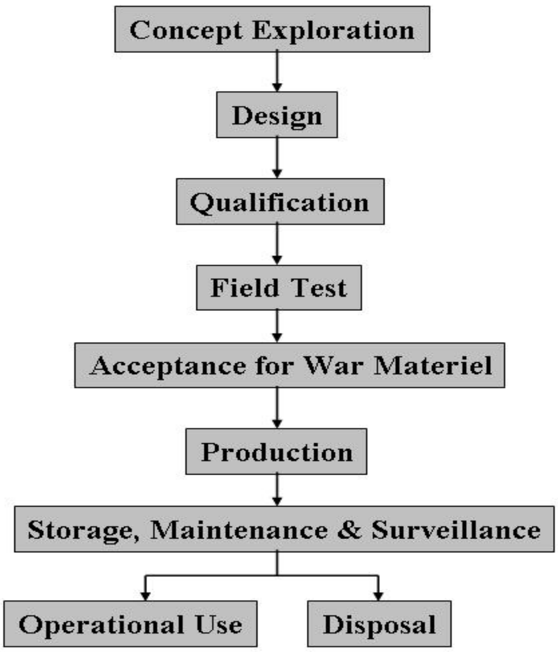

Figure 1.1. Life cycle of gun propelling charges.

1.2 Development of propulsion systems

1.2.1 General trends

The current requirements for the weapon systems and ammunition come mainly from the new army concepts, the new threats such as terrorism and asymmetric warfare. Supplementary demands also follow from the legislation regarding health, safety at work and environmental protection measures. A higher muzzle velocity is without question a continuous demand for the development of ammunition and gun systems for overcoming more and more challenging armoured targets.

Despite the abovementioned new demands, the ammunition and gun barrel have to be designed to withstand the operational use induced forces, heat and erosion taking place during firing. In the design phases of an individual propelling charge the ignition system as well as gun propellant composition and dimensions have to be optimized taking into consideration the applicable gun barrel and projectile types. The optimum pressure curves within System Permissible Maximum Pressure [7] have to be generated for all defined environmental conditions during the life cycle of the gun propelling charge. Ever higher pressures and shorter ballistic cycle also have to be taken into consideration in the development of pressure measurement techniques for gun firings. The chamber pressure measurement methods will be discussed in Section 2 of this dissertation [I].

The chemical and functional properties of gun propelling charges should be known for the whole life cycle and for taking into account the real environmental profile. The test procedures for the estimation of the chemical stability of conventional gun propellants have lately been NATO standardized [8-9]. The main lines of the FDF surveillance system of nitrocellulose (NC) propellants have been described in [10]. The FDF surveillance system was updated 2007 to take into consideration NATO standardization, but maintaining compatibility with former results. The status of the knowledge about the effect of ageing upon insensitive munitions (IM) performance, safety, demilitarization and disposal techniques for munitions and related materials has been reviewed [11-12]. The functional stability of propelling charges and monitoring of ammunition in field situations will be discussed in Section 4 of this dissertation [V].

1.2.2 Gun propulsion concepts

Several new gun propulsion concepts intended to increase gun performance have been under development in recent decades. A review of chemical, hybrid (electric/chemical) and electric/electromagnetic gun propulsion concepts has been presented by Klingenberg and co-workers [13-14].

Examples of the new chemical gun propulsion concepts are serial chamber gun [15], cased telescoped ammunition (CTA) gun [16], traveling-charge gun [3,17] and liquid propellant gun [3,14,18-19]. Despite the broad development the fielding of a liquid propellant gun system has been postponed because of combustion and system related issues.

Electrothermal-chemical (ETC) gun technology is an example of a hybrid gun propulsion concept. It attempts to utilize electrical energy in the form of plasma to augment and control the release of chemical energy stored in propellants in order to achieve significant performance enhancements using existing guns [20-25]. A less energy consuming outgrowth of ETC technology is electrothermal-chemical ignition (ETI) [26], which allows a smaller and lighter package to be fielded. US ARMY ARDEC in 2004 already demonstrated ETI technology in 120-mm firings. The advantages of plasma ignition, if fielded, could be higher loading densities, prompt ignition of propelling charges, low vulnerability, reliable ignition of insensitive propellants, and compensation for propellant burning rate variation with temperature. The consequences of the laboratory applications of ETC and ETI have been the vast efforts to better understand the ignition and combustion of the propelling charges, the formation of pressure waves in the combustion chamber of the gun and also the formation of barrel wear. Indirectly these applications have also advanced the mathematical modeling of interior ballistics.

The decreasing trend in laser costs has promoted the development of laser based ignition of the propelling charges [27-29]. Because a laser induced ignition is a result of solely energy transfer without the impact of mass transfer of hot gases, the development of the uniformity of ignition is an issue to be resolved.

The rail gun is an example of electromagnetic gun propulsion and consists of two parallel rails connected by an armature. When a voltage is applied across the breech ends of the rails, current flows through the circuit formed by the rails and the armature establishing a magnetic field that produces a force, the Lorenz force, thus accelerating the projectile [13,30-31]. The mass and size of power supply needed has until now prevented the realization of the rail gun. A comparison of design considerations of a notional railgun (muzzle velocity 2300 m/s and mass of projectile 0.090 kg) and Mauser 30-mm MK 30-2 (muzzle velocity 1405 m/s and mass of projectile 0.235 kg) with about equal muzzle energies has been presented by Tzeng and co-workers [32].

1.2.3 Propellants

Beyond the demand for ammunition with higher kinetic energy, there is a need for less sensitive, more environmentally friendly and non-toxic ammunition. Insensitive munitions (IM) [33-34] have the additional feature of minimizing the probability of inadvertent initiation and the severity of subsequent collateral damage to weapon platforms, logistics systems and personnel. Because low vulnerability ammunition (LOVA) propellants are needed for insensitive munitions, the development of both less sensitive new conventional nitrocellulose (NC) based gun propellants and composite gun propellants has been active in recent decades. Environmental and healthy concerns lead towards the development of propellants manufactured from less toxic components, with less toxic combustion products having less solid residue [35]. There is an aim to replace the toxic components of other elements of ammunition, in the first place primers.

Conventional NC propellants appear as a homogenous solid phase together with the properties of a polymeric material. Their mechanical properties enable them to be extruded or pressed together with plasticizers and other compounds to degressive, neutral or progressive burning geometric form of the propellant [36]. LOVA composite propellants, if compared to conventional NC propellants, have an additional parameter in the grain size of propellant ingredients as RDX. LOVA propellants have typically been found to be more difficult to ignite [37]. Thus the system performance of LOVA propellants cannot be maximized before their burn rate profiles, mechanical properties and gas dynamics are fully understood [38]. The LOVA propellants have been also more expensive than the NC propellants. These drawbacks with LOVA gun propellants have promoted the development of new more effective ignition methods, or as an alternative product the development of less sensitive NC based or NC bonded propellants [39-43].

The oxidizer includes the oxygen needed for ignition and burning of the gun propellant in the combustion chamber of the gun. Examples of oxidizers proposed lately for new gun propellant formulations are ADN (ammonium dinitramide) [44-46], FOX 12 (N-guanylurea-dinitramide, GUDN) [47-48], CL20 (hexanitrohexaazaisowurtzitane) and TNAZ (3,3-trinitroazetidine) [49]. To maximize the energy content of the propellant suitable energetic binder polymers have been sought. Promising energetic binders are chemically cured PolyNIMMO (poly[3-nitratomethyl-3-methyloxetane]), polyGLYN (poly-glycidylnitrate) [50-51], BAMO/NMMO-copolymer (3,3-bis(azidomethyl)oxetane/3-nitratomethyl-3-methyloxetane) [52] and GAP (hydroxy-terminated glycidyl azide polymer) [36]. Numerous energetic plasticizers to be used in solid propellants and plastic bonded explosives have lately also been experimented with [53]. Energetic plasticizers are added to propellant binder not only to increase propellant energy content, but also to lower propellant glass transition temperature below the minimum service temperature and to lower uncured propellant viscosity to improve processing. One important new feature has been achieved in Low Temperature Coefficient (LTC) propellants with dinitro diaza (DNDA) based plasticizers [41,42]. The designers of the gun propelling charges often in a dilemma of achieving the ammunition combination muzzle velocity requirement within the System Permissible Maximum Pressure (see definition in Section 2.1) would welcome the much lower temperature dependence of the chamber maximum pressure typical for the LTC propellants.

In the development and production of propellants and propelling charges the influence of the thermodynamic parameters of the propellants on the energy output and in attaining required muzzle velocities must be understood. Oxygen balance and enthalpy of formation are the most important thermodynamical parameters which influence combustion temperature, specific energy, heat of explosion and gas formation of explosives. Simmons [54], Volk and Bathelt [55] and Woodley [56] have presented demonstrations of thermodynamical calculations for conventional NC and LOVA gun propellants.

1.2.4 Gun propelling charges

The new gun propulsion technologies and LOVA gun propellants have set the frame for the development of the functional and structural properties of the gun propelling charges. One trend in propelling charge development is to simultaneously increase the charge loading density and to tailor the burning properties of the propellant using new grain structures produced by new manufacturing methods. Examples of this are co-layered and consolidated propellants. Another trend in propelling charge development is the replacement of conventional metallic cartridge cases and cloth bags with energetic combustible material, the end products being caseless ammunitions and modular charges.

Co-layered gun propellant grains consist of two or more propellants with different burn rates laminated into strips. Manning et al. [57] developed and studied the performance of high energy high performance co-layered gun propellant for a future ETC large caliber gun. The main components of these propellant formulations were RDX, Poly-BAMO/NMMO binder and nitroguanidine. Ritter et al. [58] prepared NENA

(Nitratoethylnitramine) co-layered propellant charges and test fired them from a 20-mm gun. When compared with the propellants NENA-0 and GB Pa 125 (a reference double base formulation) a co-layered composition NENA-ST-06-1 with NENA-0 as the fast burning formulation and NENA-Bu 15 as the slow burning formulation produced an increase of about 15% in kinetic energy at 400 MPa maximum gun chamber pressure. Schoolderman et al. [59] applied co-extrusion in the development of co-layered propellant.

Consolidated propelling charges consist typically of several disks consolidated from propellant grains [60] or of prefragmented propellant plates [61]. Conventional ignition usually is not adequate to create sufficient combustion of the consolidated charge [62]. The reported benefits of the consolidated propelling charges have been the possibility to increase charge mass and loading density, good progressivity and user-friendly construction.

The advantages of realization of caseless ammunition over conventional brass cased small arms would offer an ammunition weight reduction of up to 50% and a force multiplier as a consequence of decreased logistics burden [63]. Combustible cartridge material development aims at the improvement of mechanical properties and thus reduction of the web size [64].

Foamed polymer bonded propellants have been reported to be suitable for the production of caseless ammunition or combustible cases [65-68]. Their interior ballistic behavior can be varied in a wide range merely by changing the formulation and by adjusting the interior porous structure. Böhlein-Mauss et al. [69] improved the mechanical properties of foamed propellants by optimization of the manufacturing process in order to prevent gas-slipping during the interior ballistic phase.

The serial production of modular charges for artillery gun systems began in the 1990s. The modular charge is composed of several modules i.e. containers produced of rigid combustible material containing the main propellants and a center core igniter [70]. The advantages of modular charges are robustness, easy handling, fast loading and the option to use usually one to six modules according to the recovery zone [71]. In the course of modular charge development some hazardous drawbacks with stickers have become apparent i.e. the projectile stopping during the engraving process with low zones [72-73]. Muzzle velocity well above the sticker must be reached by modular charges designed for all zones.

The combustible cartridges which comprise the propelling charge of the mortar system facilitate the preparation of ammunition and simplify round assembly. In addition an approximately 6-7% contribution of combustible cartridge material to the interior ballistics of mortar system has been reported [74].

In contrast to earlier applications a base bleed unit is a composite propellant containing a gas generator mounted on the projectile base in order to increase the trajectory by about 30% by compensating the base drag during projectile flight [3]. Base bleed units have been in serial production since the early 1980s. According to the headlines of Jane's Defence Weekly (26 April 2006) an extended range of 75 km has been reached by the Denel G6-52L 155-mm self-propelled gun using velocity-enhanced long-range artillery projectiles (V-LAP) with both base bleed unit and rocket assistance.

1.3 Recent developments connected to the interior ballistic cycle

1.3.1 Mathematical modeling of interior ballistics

During the past few decades the field of interior ballistics has been greatly advanced by the development and application of several equations describing mathematical models differing in complexity of coding structure and method of solution of fluid motion. The improved performance of computers has allowed the development of ever more detailed multidimensional (multiD) modular mathematical codes capable of treating several types of gun propulsion systems based on solution of the conservative equations [75-76]. By conservation equations for mass, energy and momentum the variations of fluid pressure, temperature, density, velocity, composition etc. can be described throughout space and time. These equations for total mass, momentum, energy and mass of species in chemical reactions are difficult to solve in their most general form, but Computational Fluid Dynamics (CFD) enables their practical solution. In order to accommodate turbulence and to enlarge the examined length scale from the level of individual propellant grain, the governing nonlinear partial differential equations are formally averaged to follow the average properties of flow. For example in the finite-difference solution the partial derivatives appearing in the conservation equations are then replaced with algebraic difference quotients i.e. discretized, yielding algebraic equations for the flow field variables at the specified grid points. In addition to turbulence, the phase transformations and chemical reactions as well as boundary conditions have to be carefully taken into consideration in the modeling of interior ballistics.

The most simple interior ballistics codes are zero-dimensional (0D) or lumped parameter models based on the assumption that grains and the products of combustion constitute a well-stirred mixture. 0D models are suitable for the prediction of global parameters like peak pressure and muzzle velocity. Examples of 0D codes are IBHVG2 (U.S.A) [77], the ETC version of it IBHVGETC (U.S.A) [78-79], TIBALCO (the Netherlands) [80] and TMIB (Finland). The construction and application of the TMIB code is presented in [81].

One-dimensional (1D) interior ballistics codes are able to solve numerically pressure and velocity as a function of the axial coordinate and time. After the needed input data have been collected the calculation can usually be carried out in few seconds by a personal computer. 1D codes are suitable for routine research and development purposes, for example for the prediction of global parameters or as diagnostic tool of processes taking place in combustion chamber. The first version of the 1D NOVA code (U.S.A) was introduced 1980 and an improved version XNOVAKTC or XKTC in 1990. Later on it was extended to the NOVA family applicable to a variety of solid propellant configurations [82-83]. Further examples of 1D codes are AMI1D and AMI1D NG (Germany) [84], CTA1 (U.K.) [78,85-88] , FNGUN (U.K.) [89-91], MOBIDIC (France)

[71,82,92], TWOPIB (Yugoslavia) [93] and WAFBC1CHEM (U.K.) [85,94]. CTA1 and WAFBC1CHEM differ in propellant heating and ignition models.

Complicated propelling charge constructions can only be simulated by using two-dimensional (2D) or multiD from two to multiphase flow models [79,95]. Complicated propelling charge constructions involve, for example, multiple non-stationary increments and complex distributions of ullage, the effects of which are non-uniformities in certain interior ballistic events as ignition, flame spreading and pressure wave generation. The application of 2D and multiD models is limited to research purposes, because a calculation grid has to be developed for each case, detailed input data have to be designed and calculation run times are long even using super computers. Gough [76] in 1993 presented a formulation of the equations, the solution of algorithms, and the implications of the trend toward parallel computing for a next-generation interior ballistic code (NGEN). NGEN has been designed to be capable for treating several charge designs (also liquid propellants and ETC). A two-phase flow model MOBIDIC-NG 2D (France) has also been designed for several charge designs [96]. There is an ETC version M2DNGETC of MOBIDIC-NG [97]. A 3D fluid-mechanical, reactive, multi-phase tensor-based object-oriented model FOAM has been programmed in Sweden [98]. In South Africa an interior ballistic model has been coded [99] and later another model developed by adding a reactive second phase to the commercial CFD code FLO++ [95]. ABACUS (U.S.A) [100] is a FEM model application for the launch dynamics of the Excalibur projectile. Ray and Tezduyar [101] have presented an early study of a fluid-object interaction model for an advanced chemical propulsion system. Further 2D or multiD interior ballistics codes are AMI2D and AMImultiD (Germany) [84], CRAFT (U.S.A.) [102], FHIBS (U.K.) [85,103], PISCES [92,104], QIMIBS (U.K.) [105] for mortars and TDNOVA [106].

Examples of the application of interior ballistic codes are presented in Chapters 1.3.2, 1.3.3 and 1.3.4. Comparisons of prediction capabilities of interior ballistic codes are reviewed in the following. Woodley et al. [107] carried out standard test case simulations using codes CTA1, WAFBC1CHEM, FHIBS, IBHVG2, AMI1D, AMI2D,

AMI1D NG, MOBIDIC-NG (1D), MOBIDIC-NG (2D), SIBIL (0D, France) and XKTC. The non-compliance of sub models of codes for interphase drag and intergranular stresses was reported to be the main reason for the wide variation in the resulting maximum pressures and muzzle velocities. Very little difference was observed in the ignition phase results, which refers to the similarity of propellant heating modes. Wildegger-Gassmaier [108] compared codes IBHVG2 and XKTC in describing the influence of horizontal and coaxial layering of propellants having different burning rates and grain geometries on the interior ballistic performance in a 30-mm gun. Heiser [84] compared the capabilities of codes IBHVG2, XKTC and AMImultiD in predicting the cycle of propulsion and to estimate system performance of the two simple granular charges and of a modern ETC-system.

The mathematical modeling of interior ballistics using commercial interior ballistic software FNGUN has been introduced in the FDF and in the Finnish defense industry in the 2000s. The modeling has been applied, for example, to charge design, charge establishment and in solving unexpected events during firings. As a result more information of the ballistic behavior of the charge to be determined is available before charge establishment firing and it has been possible to reduce the number of charge sizes to be test fired.

More advanced modeling of interior ballistics has also taken place in Finland by applying the parallel multiblock flow solver FINFLO [109] developed by Helsinki University of Technology Laboratory of Aerodynamics. For example, the burning of base bleed units has been modeled with FINFLO [110].

1.3.2 Ignition and combustion of the gun propelling charges

Empirical methods have traditionally been used in primer design. There are two main reasons for the demand to better understand how the primer ignites the main propellant of the propelling charge. Pressure waves have several times been discovered in large caliber artillery propelling charge design. Recently there have also been drawbacks in the ignition of LOVA gun propellants. Therefore the propellant ignition phenomenon and especially plasma-propellant interactions have been studied intensively in recent years.

Chemical propulsion of black powder, black powder/NC-propellant or porous NC has been a principle of conventional propelling charge igniters (primers) and booster charges. The influence of conventional igniter system configuration on pressure wave behavior, ignition delay and temperature dependence have been studied by Gassmaier and Johnston [111] for granular LOVA-propellant bed and by Steinman et al. [112] for EI® propelling cartridges in 25-mm rounds. The principal component of EI® propellants is nitrocellulose, but these are de-mobilized by an impregnation process. According to Su [113], the increase of hot gas pressure reduces the ignition time of a solid propellant. This is a result of an increase in the coefficient of heat convection and heat flux. However, the increase of hot gas velocity will reduce the gas temperature and lead to longer ignition delay. Jaramaz [114] has developed and verified a theoretical model of flame spreading through the granular propellant bed during base ignition.

Different theories have been presented regarding the role of radiation, convection and type of plasma (metallic, organo-metallic or electric) in the energy transfer of plasma ignition. The reasons for higher burning rates observed for transparent propellants if compared to opaque propellants have also been widely discussed. The progress of plasma ignition research has been reported by Proud and Bourne [115], Beyer et al. [116-117], Fuller and Taylor [118], Woodley [119], Koleczko et al. [120-121] and Lombard et al. [97].

Because of plasma ignition the interior ballistics models have to be upgraded according to Légeret et al. [122] on the areas of thermodynamic parameters, burn rate coefficient of propellant grains and energy equation of convective and radiative heat transfer between propellant grains, gases and the wall. They have divided the interior ballistics calculation into steps of plasma injection, interaction between the working fluid and propellant grains, and classic combustion. They have also reported plasma ignition to increase the propellant burning rate about by four times during plasma-propellant interaction and to some extent also afterwards.

Fischer and co-workers [68] carried out closed vessel experiments for conventionally ignited foamed propellants. They demonstrated the marked influence of propellant porosity profile on the burning properties. Vieille’s law [2] has been modified to take into consideration the temperature dependence of the combustion in porous propellants. If compared to graphite coated JA2 propellant they found that transparent propellants plasma ignited in closed vessel had much higher burning rates as a result of in-situ generated porosity. Closed vessel studies of plasma ignition have been reported by Lombard et al. [97], Taylor and Woodley [123], Kooker [94] and Chang et al. [124].

The option to use high temperature pyrotechnics instead of black powder or ETI in the ignition of LOVA propellants was studied by Taylor and Gransden [125]. Their group intends to study the suitability of thermites, which generate a metal vapor, for use in large caliber gun ignition and their ignition behavior compared to electrothermal plasma or black powder [126]. We have to wait if the traditional ignition with black powder or porous nitrocellulose (NC) can, where effective ignition is needed, be replaced with fielded ETI or with the new chemical igniters (pyrotechnics or thermites). It should be noted that the introduction of high temperatures in the ignition phase can lead to the increase of barrel wear and to barrel flash formation because of the high temperature of the combustion gases.

1.3.3 Pressure waves

The occurrence of pressure waves in large caliber guns has lately been one of the most studied issues in the field of interior ballistics [3]. Strong ignition pulse, high loading density, grain breakup and high loading density and unsuitable intrinsic burning properties and/or geometry of the propellant are risk factors with the potential to cause violent burning or even transition from deflagration to detonation [127-128]. Using base ignition Weng et al. [129] showed that a proportion of 2.5% of fractured propellant grains clearly raised maximum pressure, and 3% caused a breech blow. In the same study the use of center core igniter reduced the tendency to pressures waves. Yang et al. [130] reported the intergranular stresses during the engraving process to be higher for granular propelling charge formulations if compared to tubular, or tubular and granular propelling charge configurations. At low temperatures the probability of grain fracture increases because of the brittleness of propellant. Briand et al. [131] reported a breech blow case as a result of an ignition delay caused by wear-reducing agent coating of propellant grains.

According to Sanghavi et al. [132] the mechanical properties of conventional NC propellants can be improved, and the risk of grain break mitigated, by careful selection of nitrocellulose and by incorporation of additional plasticizers. Contrary to NC propellants, the viscoelastic behavior of composite propellants is not only determined by the properties of the polymeric matrix, but also by the interaction of the matrix with the filler surface and by filler-filler interaction [133]. Severe problems during the service of composite gun propellants may occur as a consequence of the detachment of the matrix from the filler surface, reorientation of polymeric chains, breakages of filler particles and filler-filler interactions in tension and compression. The evaluation of the mechanical properties of a propellant should be based on the consideration of Poisson's ratio and stress-strain curve at the same time. According to Kooker et al. [134] a plastic deformation is the dominant compaction mechanism of granular gun propellant grains, and solid bulk compressibility plays an important role in a quasi-static compression. In the early interior ballistics codes the mixture porosity was assumed to be incompressible solid phase (for example in XNOVAKTC code). Heiser and Wolf [135] in the dynamic loading simulations found different deformation behavior for conventional JA2 grains if compared to M14, M30A1 and M43 propellant grains.

In the following two examples mathematical codes have been used to find the causes of pressure wave formation. Woodley [87] applied modified CTA1 code for studying the ignition of the primary cartridge in the mortar tube. The roles of propellant ignition in the primary cartridge and the subsequent bursting of the cartridge wall material were studied. The propellant movement caused by spatially unbalanced ignition in the primary cartridge was found to be a major source of pressure waves in this region. The magnitude of the pressure waves could be reduced substantially by using different diameter and/or distribution of vent holes in primary cartridge. Moreover, Woodley [86] modeled both ETC 155-mm gun firings with unimodular propelling charge and ballistic simulator experiments with plasma ignition and inert propellant. Severe pressure waves appearing in zone 4 gun firings could be reduced to very small by replacing the 500 kJ ignition energy by 100 kJ. The pressure waves could be simulated only if enhanced combustion was assumed in the first module. Inspection of the predicted velocities indicated that the propellant could be shattered at impact on the projectile base. It was shown that both strong conventional and plasma ignition could lead to pressure waves.

At present the formation of pressure waves in the gun combustion chamber is most often studied as a part of propelling charge development. In the generally applied method [136] pressure curves are measured at the breech and forward section of the combustion chamber and the difference between these two pressure curves is evaluated. Schabort [137] drafted an alternative method for characterization of pressure wave activity in artillery gun systems. This method is based on the digital signal processing principles and involves pressure wave extraction from a single measured piezo breech pressure curve.

1.3.4 Barrel wear, heat transfer in the barrel and projectile travel

Gun barrel erosion has been defined as the progressive damage of the bore surface and enlargement of the bore of a gun barrel by normal firing, ultimately resulting in loss of muzzle velocity, range, and accuracy and therefore the effectiveness of the weapon [3]. Thermal factors play a significant role in gun barrel erosion when they are associated with chemical and mechanical factors. In isolation the thermal factors can lead to thermal softening of the bore surface, thermal phase transformation in the bore surface, and melting of the bore surface.

Combustion gas pressure causes cracking in the bore surface and bore expansion. The mechanical sweeping action of the propellant gas stream removes material from the bore surface. The reactive hot gas flows in gun barrels cause three reaction zones within the barrel surface layer: a white layer zone, a thermally affected zone and a bulk zone [138]. The chemical reactions that occur at the bore surface, and the rate at which they proceed, depend on the type of propellant used and on the temperature of the gas mixture. Arisawa and Kimura [139], on the basis of gas erosion bomb studies for LOVA [140] and conventional (single, double and triple base) propellants, developed a gas erosion simulation technique. The hydrogen gas content minimizing the hydrogen gas erosion of high-energy LOVA propellants was found to be about 13 mol% and adiabatic isochoric flame temperature about 2800 ^{o}C to 3000 ^{o}C. In a preliminary study Hordijk and Leurs [80] found a low pressure vented vessel to be suitable for the examination of differences in the erosive properties of TPE/RDX or ETPE/RDX based LOVA propellants and NC based gun propellants.

The method to measure barrel wear applied by the FDF is described in [II]. The importance of the correct definition of barrel wear coefficient during propelling charge design will be discussed in Section 3 of this dissertation. Zimmermann and co-workers [141] presented a method to study gun barrel wear by erosion sensors. Measurements were carried out using fitted steel probe elements into the bore-holes.

Crowley et al. [142] developed an engraving model of the worn gun. In the model developed the forcing cone angle, the area of the forcing cone and the diameters of the bore in the grooves and lands are taken into account as a function of the number of rounds fired.

Besides thermal damage and wear of the barrel the increased firing rates applied to advanced gun systems cause a safety risk of charge or projectile cook-off. This risk is assessed by a slow cook-off test [143] as a part of the tests for safety and suitability for service (S^3) [6] in the design phases of a propelling charge.

Calculation of the heat transfer to the gun barrel during the interior ballistic cycle has been demonstrated by Horst et al. [83]. Heiser and co-workers [144] have presented a numerical and an analytical approach for the calculation of the role of boundary layer in the heat conduction to the gun barrel during the interior ballistic cycle. Their numerical approach consisted of a full Navier-Stokes solution of conservation equations including turbulence and heat flow. Their analytical approach was based on Prandtl's boundary layer equations. According to Boisson et al. [145] the radiative heat transfer to the gun barrel during the firing is much lower if compared to the convective option. However, during the cooling phase of the barrel the radiative heat exchange is as important as the convective phase.

Gallier et al. [146] used interior ballistics code MOBIDIC-NG and erosion code COPEC in the calculation of the heat and mass transfer to the gun barrel, surface temperature of the barrel and rate of removal of barrel steel due to melting and chemical attack. The barrel wear and heat transfer to the barrel during the interior ballistic cycle were also studied and modeled by Gao et al. [147] and with coverage of several gun propulsion concepts by Boisson and co-workers [148-151] and by Lawton [152-154].

There have been attempts to replace conventional steel as a gun barrel liner material, but for the time being without a breakthrough. The expected advantages of ceramic gun barrel technology would be excellent erosion resistance and the ability to withstand high temperatures without degrading. The U.S. Army Research Laboratory (ARL) has developed a material property database of commercially available ceramics and carried out extensive finite element and analytic modeling of ceramic gun barrel technology. The ARL has also developed a model of the generation of failure surface plots to investigate optimal geometries and prestress levels of different liner and sheath materials for various caliber systems [155]. The ARL has moreover planned ballistic testing with commercially available ceramics, utilized probabilistic failure modeling to assess the viability of ceramics, and developed multi-axial confinement schemes for tests under ballistic conditions [156].

The jacket or rotating band of the projectile exerts pressure on the bore surface as it moves down the gun barrel [3]. Projectile driving band interactions with gun barrels during the launch phase can be analyzed with commercial finite-element stress analysis codes. With effective sealing of propellant gases during the early stages of the interior ballistics phase high in-bore velocities can be reached, but at the expense of increased wear on the driving band. The increase of strength of the driving band material can reduce wear, but may also impair sealing [157]. Suth and Newill [158] studied the obturation of the M855 projectile in an M16A2/A3/A4 rifle. Based on FEM simulations they localized the obturation to occur at both the front and rear parts of the cylindrical section of the projectile. Snyman [159] calculated the coefficient of friction and the frictional force of a moving projectile inside a barrel. He applied lubrication theory using axisymmetric hydrocode HEX.

Andrews [160] used strain gauges to monitor the effect of the driving band on the barrel during firing trials of 155-mm guns. He found that the lower charge zones generated even twice the exterior strain expected from the gas pressure of the top charges. The load was reduced because of more degradation of the driving band with top charges. The suitability of strain gauge methodology for barrel pressure measurement has been studied in the gun and mortar test firings in Finland [161].

1.4 Scope of the work

This dissertation is connected to the outsourcing of the design and production of gun propelling charges in the FDF. This outsourcing has been ongoing in cooperation of the FDF with the Finnish defense industry during the 2000s. As a procurer it is important for the FDF to continuously improve the know-how of the procedures concerning the life cycle of gun propelling charges. The goal of FDF is to carry out procurement, storage, maintenance, use and disposal of the propelling charges in a competent, cost-effective, safe and ecological way.

The aim of this dissertation was to examine, improve and, when needed, develop new procedures and measurement methods connected to the life cycle of gun propelling charges. The main stress was on the improvement of quality and safety of the procedures. The study comprises three case studies.

New technology allows ever more effective ways to collect, store and process data [162]. In the FDF data collection and storage in the databases takes place during each test firing occasion. The utilization of this data is usually restricted to the needs of the test firing occasion in question, although the use of the data could possibly be more effective and the data could be used, for example, for quality purposes. In FDF conscript practice troop firings several thousand artillery rounds are fired annually. Stored information about these rounds fired could have many applications. The approach of this dissertation was a statistical utilization of the results collected in test or conscript practice firings. Characteristic for the firing results analyzed in this dissertation was that the firings had been organized independently of this study. All the firings to be discussed in this dissertation were carried out with guns, gun propelling charges and projectiles accepted as war materiel by the FDF.

Proper pressure measurement is a necessity in test firings if the performance of the propelling charge is among the test objects. The FDF and the defense industry have found challenges in the definition of the accurate permissible maximum pressure values for cannon, projectile and gun propelling charges. These values must be defined in the design phases of the gun and ammunition system [7]. One long-term issue has been the inadequate knowledge about the equivalence of the real pressure in the combustion chamber to the reported peak pressure values from test firings. In Case I of this study the dynamic calibration method developed for crusher pressure gauge elements was verified and implemented. The methodology for verification was based on analysis and modeling of the pressure results of artillery test firings. Case I is presented in Chapter 2 [I].

Several 155-mm gun propelling full charge lots procured by the FDF and test fired during the years 1999 - 2003 had not met the acceptance requirements. Hence, it was necessary to study if defects could be found in the design or production or test firing phases of the gun propelling charge type in question. There was a particular need to examine the performance of the test procedure for determining artillery gun propelling charge weight. In Case II of this study the reasons for high occasion-to-occasion and lot-to-lot variation of muzzle velocity for gun propelling charges present in the results of test procedure for determining 155-mm gun propelling charge weight were studied. The methodology applied was multivariate analysis. The data set consisted of propellant lot related data collected during propellant lot production and a procedure for determining gun propelling charge weight. Case II is presented in Chapter 3 [II-III].

It has been anticipated that information about the functional life of gun propelling charges could be achievable by collection of muzzle velocity data in conscript practice troop firings. Case III of this study reports the development and implementation of a surveillance system for gun propelling charges utilizing conscript practice troop firings. The system is based on muzzle velocity data collection for each round fired. The methodology applied was the statistical evaluation of muzzle velocity data collected during 155-mm weapon system troop firings. Case III is presented in Chapter 4 [IV-V].

2 Case I: A dynamic calibration method for crusher gauges based on material testing

2.1 Introduction

The reproducibility of correct results of pressure measurements from combustion chamber is a challenge in test firings. Pressure measurements in test firings using the crusher gauge method have been carried out by the FDF for several decades. In this pressure measurement method the gas pressure is applied via a piston to a copper element contained within the gauge body. The crusher and piezo-electric pressure measurement methods are presented in more detail in [I].

After the introduction of the piezo-electric pressure measurement method by the FDF, a systematic difference between reported piezo-electric and Handke 28-5 crusher gauge (manufactured by Wilhelm Handke GmbH, Pommernstr. 6, D-83395 Freilassing, Germany) peak pressures was observed. The reported piezo-electric values were higher at peak pressures exceeding about 150 MPa, as confirmed by Järviniemi [163]. The peak pressure difference has been proven to originate from the static calibration tables used instead of dynamic calibration tables for the Handke 28-5 crusher gauge. The crusher element is based on the proportionality of the gun pressure and the amount of plastic deformation of the crusher element. This proportionality, however, is nonlinear because the work hardening behavior of metals is a function of both strain and strain rate. This phenomenon is not taken into account by the static calibration tables, which are defined according to slow pressing of the crusher element. On the contrary the dynamic calibration tables are based on crusher element testing with high strain rates.

The difference in reported peak pressure values discussed above has caused uncertainty in the FDF and Finnish defense industry particularly in the context of definition and application of permissible maximum pressure values according to STANAG 4110 [7]. The mechanical design pressure values Cannon Design Pressure (Cannon DP) and

Cannon DP Curve should be based on the Ballistic Design Pressure Curve derived from preliminary interior ballistic modeling. DP chamber pressure values of cannon or projectile should not be exceeded by more than one round in 1,000,000 rounds under extreme service conditions. In the concept exploration phase the gun propelling charge developer is provided with the System Permissible Maximum Pressure (System PMP) value, which is the lower value of Cannon PMP or Projectile PMP defined for a specified system. Cannon or Projectile PMP chamber pressure values should not be exceeded by more than 13 rounds in 10,000 under extreme service conditions. System PMP value is an important frame setter for gun propelling charge interior ballistic design. The definition of Extreme Service Condition Pressure (ESCP) is the chamber pressure developed when firing the specified system under extreme service conditions. Maximum Operation Pressure (MOP) is the ESCP plus three times the corresponding pressure standard deviations estimated during the cannon design phase. MOP has to be equal or lower than System PMP. The corresponding pressure standard deviations coming from round-to-round, gun-to-gun and occasion-to-occasion have to be estimated during propelling charge design.

The peak pressure values lower than real reported for crusher gauges could have caused safety issues. This risk cumulated in cases where the System PMP had been based on real pressure and the MOP on the crusher gauge results reported based on static calibration tables.

The long experience of use and large pool of stored results spoke against the withdrawal or replacement of Handke crusher gauge 28-5 type without thorough study. The aim of Case I was to develop the capability to present results measured by a Handke 28-5 crusher gauge based on both the traditional static tables and the new dynamic calibration tables.

A new dynamic calibration methodology capable of the dynamic calibration of crusher gauges covering a wide range of fundamental variables, stress (pressure), stress rate and temperature, has been developed in Tampere University of Technology. This methodology is based on material testing of crusher gauge elements with a Hopkinson Split Bar (HSB) device at high strain rates and servo-hydraulic materials testing machine at low and intermediate strain rates. For the theoretical background of the strain rate dependence, the laboratory measurements of crusher elements as well as the modeling the reader is referred to publication [I].

Other applications of HSB methodology related to weapon systems have also been reported recently. HSB methodology has been applied to the examination of the physical behavior and shear initiation of explosives and solid propellants subjected to pressures [164]. Another application of HSB methodology concerned accelerations/decelerations during gun launch and penetrator impact [165].

The verification of the dynamic calibration methodology developed was carried out by the comparison of dynamic calibration model with the piezo-electric peak pressure records and crusher pressure values obtained from live test firings for several weapon systems. The pressure rise times for different round combinations were also taken into consideration in the verification.

2.1.1 Dynamic calibration model based on material testing

Based on the records of material testing for one lot of Handke 28-5 5 x 7 mm cylindrical crusher element the dynamic calibration model (Eq. 2.1) with parameters A (Eq. 2.2) and B (Eq. 2.3) was developed.

$$\sigma_T(\varepsilon_T) = A(\varepsilon_T) + B(\varepsilon_T)\ln\left|\dot{\varepsilon}\right| \tag{2.1}$$

$$A(\varepsilon_T) = \frac{43.940 + 2455.959\left|\varepsilon_T\right|}{1 + 4.887\left|\varepsilon_T\right|} \tag{2.2}$$

$$B(\varepsilon_T) = -0.572 + 19.997\left|\varepsilon_T\right| - 11.001\left|\varepsilon_T\right|^2 \tag{2.3}$$

where

σ_T True stress, (MPa)

ε_T True strain

$\dot{\varepsilon}$ Strain rate (s^{-1})

The dynamic calibration table is presented graphically in publication [I] as $\sigma\ vs.\ \ln|\dot{\varepsilon}|$ plotted at constant values of strain from 3% to 43%.

2.1.2 Verification of the dynamic calibration model

Verification of the dynamic calibration model developed was carried out by comparing the test firing piezo-electric peak pressure records with the crusher pressure values obtained from the dynamic calibration model as a function of static crusher pressure values. The data used in the verification consisted of 1,126 piezo-electric and static crusher peak pressure records collected for several weapon systems and nine ammunition rounds in artillery test firings. The weapon systems studied were 122-mm howitzer, 130-mm cannon, 152-mm cannon, 155-mm cannon and 155-mm NATO cannon. For details of the data and for graphical presentation of the pressure data the reader is referred to publication [I]. A rational function (Eqn. 2.2) of similar form to that used in calibration model development was fitted to the piezo-electric and static crusher peak pressure data. The resulting verification model is presented below.

$$P_{cr} = \frac{-30.588 + 1.3738\,P_h}{1 + 0.0013\,P_h} \tag{2.4}$$

P_{cr} Static crusher peak pressure (MPa)

P_h Piezo-electric peak pressure (MPa)

One aim of Case I was to compare the effect of pressure rise rates realized in test firings and the dynamic calibration model strain rates in gaining pressure (or stress) values and crusher element compression (or strains). For this, the pressure rise rates of different rounds were determined from 303 piezo-electric pressure curves. A preliminary analysis of the pressure curve data for artillery weapon systems discussed in publication [I] had been reported in two studies [166-167]. Based on the pressure curve data analysis for true compressive strains ranging from about 5% to 20%, the strain rate range in the copper crusher element was from about 7 to 60 s^{-1}. The corresponding pressure values range was from about 140 to 380 MPa.

The fitted verification curve based on Eqn. (2.4) is presented in Figure 2.1 as a difference between piezo-electric and static crusher pressure as a function of the piezo-electric peak pressure. Dynamic crusher peak pressures were calculated for strain rates 10, 35 and 80 s^{-1} from the dynamic calibration table (Eqn. 2.1). The differences between these dynamic crusher peak pressures and static crusher pressures as a function of the piezo-electric peak pressure are also shown in Figure 2.1.

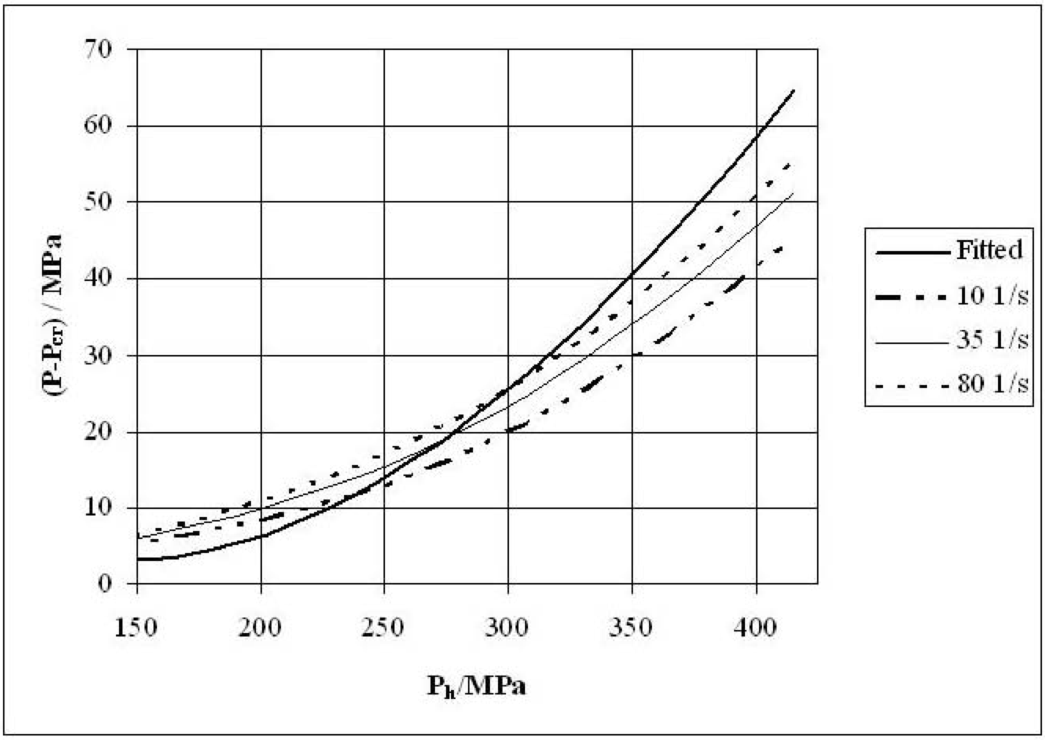

Figure 2.1. The fitted verification curve as a difference between piezo-electric and static crusher pressure (full line) and the difference curves between dynamic crusher peak pressures for strain rates 10, 35 and 80 s^{-1} and static crusher pressures as a function of the piezo-electric peak pressure.

It can be seen from Figure 2.1 that the difference between the fitted verification curve and the dynamic crusher model is negative and quite small at low pressures, i.e., the model gives slightly conservative pressure values. At higher pressures, the difference becomes positive, i.e., the dynamic crusher model values start to fall behind the fitted verification curve. The difference is smaller when a higher strain rate is applied in the dynamic crusher model, which is consistent with the fact that a higher maximum pressure also generally leads to a higher strain rate. At 400 MPa, the difference between the dynamic crusher model and the fitted verification curve varies between 8 and 18 MPa. This is much less than the difference between the static crusher and fitted verification curve at 400 MPa: about 60 MPa.

The uncertainty of the pressure measurement is relatively high, which is discussed in more detail in publication [I]. In addition to this there were only small differences observed in pressure rise times and narrow peak pressure bands for most of the rounds examined in the verification data. As an outcome of these factors it was not possible to distinguish the precise influence of pressure rise time on static crusher peak pressure values in the verification test firing data.

2.2 Conclusions

A dynamic calibration model based on laboratory material tests was developed for one Handke 28-5 5 x 7 mm cylindrical crusher element lot and verified by comparison to totally independent test firing results. The dynamic crusher pressure model developed was found to give pressure values which are consistent with the pressure records from actual test firings, especially when the general limitations in the measuring accuracy of the piezo-electric and crusher methods are taken into account.

The methodology developed in this study allows the FDF to present the crusher pressure records on the basis of both static and dynamic calibration tables. As a result the traceability of the static results so far remains and better comparability of the results with piezo-electric peak pressures is achieved.

The material testing method presented in this study is isolated from the test firings and the piezo-electric pressure measurements and also takes into account the strain rate in the deforming of the crusher element. This differs from the dynamic calibration methods for crusher gauges presented in AEP-23 [168], which are based on modeling of the records of large caliber gun firings and laboratory simulations. Contrary to the method presented in Case I these laboratory simulations have limitations at the high pressures needed for tank gun purposes, lacking controllability of stress rates and also difficulties in the coverage of low temperatures. The high price of test firings limit the round number and assortment of charge types fired in connection of calibration.

3 Case II: Multivariate analysis applied to test procedure for determining charge weight

3.1 Introduction

On the basis of the propelling charge weight establishment, the propellant weight to fulfill the muzzle velocity requirement is determined in the standard conditions defined for the round and weapon system in question. At the same time it is ensured that the defined permissible maximum pressures are not exceeded and that there is enough space to pack adjusted propellant weight in the combustion chamber. Charge weight establishment is carried out for each propellant lot. The capability of produced charge with adjusted charge weight to fulfill muzzle velocity and muzzle velocity distribution requirements in standard conditions without exceeding defined maximum pressures is confirmed on the basis of the results of the uniformity test firings.

Charge establishment has been stipulated by NATO standardization [136,169]. As a rare example of a recent treatment of this topic in the literature Ritchie et al. [170] studied the possibility of replacing expensive charge establishment test firings and even uniformity tests with the use of a ballistic simulator. Their method is based on gun propellant performance prediction with results obtained by a ballistic simulator built around a 105-mm howitzer system. Using this method, changes in 120-mm gun performance due to propellant characteristics were successfully predicted for the two ammunition rounds with several propellant lots studied for each.

Wider than expected variation in muzzle velocities was discovered by the FDF in the 155-mm charge weight determination and uniformity test firings. The reasons for this variation had been sought before, variable by variable, and separately for each test firing. It was also known that there were some weak points in the applied test procedure for determining charge weight presented in Figure 3.1. Symbols of variables in Figure 3.1 are explained in Chapter 3.2.1.

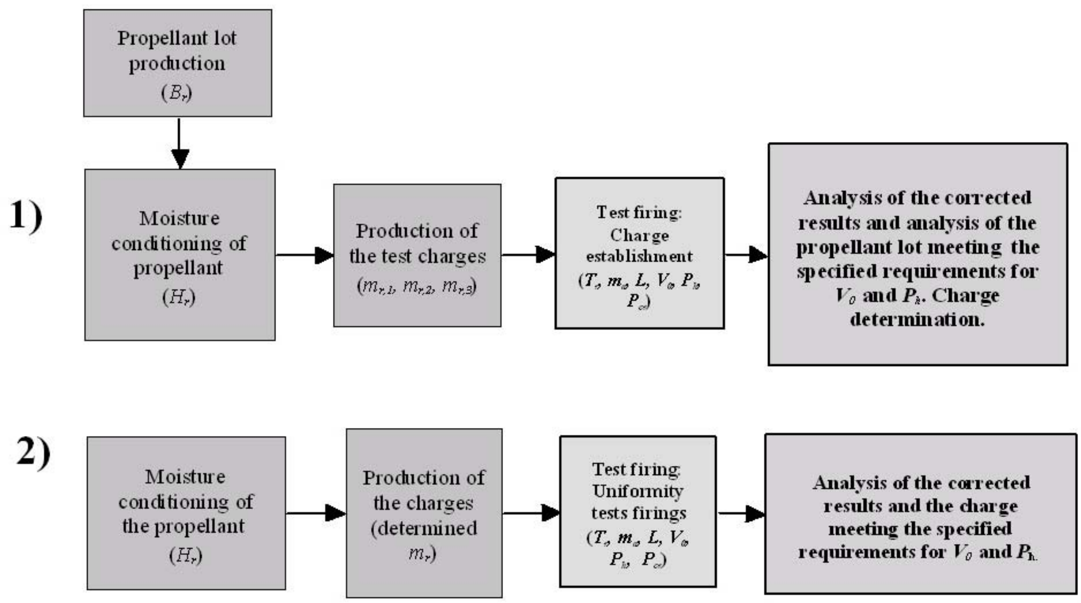

Figure 3.1. FDF test procedure for determining gun propelling charge weight: 1. Charge establishment, 2. Uniformity tests. Collection points of the variable values are presented in parentheses.

The aim of Case II was to find and evaluate the reasons for the wider than expected variation in muzzle velocities in 155-mm charge establishment and uniformity tests. Another aim was to improve the test procedure for determining charge weight. Multivariate analysis was applied as an alternative approach to the conventional analysis method to a data set consisting of results connected to 68 test firing occasions. The data matrix consisted of propellant lot specific observations with variables containing information of propellant properties and records measured during charge establishment and uniformity test firings. In publication [II] principal component analysis (PCA) [171-173] was applied to obtain an overview of the data. In publication [III] partial least squares models (PLS) [174-176] were applied in the evaluation of the data.

Multivariate analysis is applied in increasing extent also in the field of explosives, mainly on the calibrations in chemical analysis, but also other applications have been reported. As an example of the first mentioned type of application, multivariate compositional analyses of FTIR spectra for three novel propellant powder systems have been carried out using the partial least-squares (PLS) regression algorithm combined with semi-synthetic sampling [177].

Schädeli et al. [178] reported three examples of application of chemometrics for multivariate modeling of propellant manufacturing. In their first example chemometrics was applied to the process control of nitrocellulose manufacturing in order to compensate propellant ballistic property fluctuation. Their second application was the propellant process parameter optimization to tailor temperature characteristics for muzzle velocity of propelling charge. In their last example the impacts of chemical composition, geometrical factors and propellant manufacturing parameters for Bergmann-Junk stability test results were studied.

Niehaus and Greeb [179-180] applied multiple regression analysis in the optimization of propellant binder systems. The mechanical properties of the binder were predicted as a function of composition. The main components of propellant binders systems studied were GAP and nitrocellulose. Petrzilek et al. [181] also applied multivariate analysis before presenting the burning rates of homogenous solid propellants at the pressures ranging from 1 to 15 MPa.

3.2 Results and discussion

3.2.1 Preliminary analysis

An overview of the data set was obtained by a preliminary PCA analysis for the variables temperature of the propelling charge (T_r), weight of the main propellant (m_r), relative vivacity of the propellant lot (B_r), moisture content of the main propellant (H_r), projectile weight (m_a), barrel wear (L), number of rounds (L_{sm}), loading distance (L_{lat}), muzzle velocity of the projectile (V_0), peak chamber pressures measured by the piezo-electric method (P_h) and crusher method (P_{cr}), recoil length (S_r) and retardation (k). For details about samples, data set and the characteristics of the data set the reader is referred to publication [II] and for the measurement system to Figure 1 in publication [III].

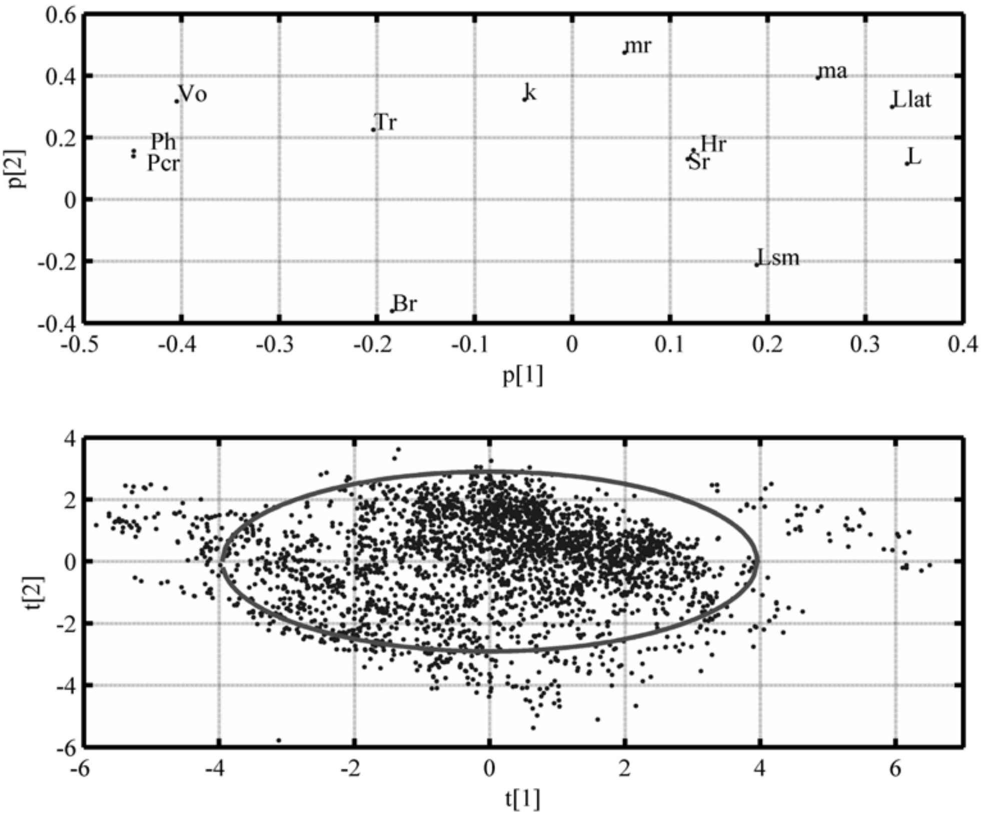

Figure 3.2 Loadings and scores for the first and the second principal components and Hotelling's ellipse.

Loadings and scores for the first and the second principal components and a 95% confidence region for the scores (Hotelling's ellipse) are presented in Figure 3.2. The loadings and scores give information about correlations between variables and the impact of each variable on the model. The percent variances for five first PCs were 30%, 18%, 12%, 11% and 7%. The main finding of the PCA results was the lower than expected correlation between the variables loading distance (L_{lat}), round number fired (L_{sm}) and barrel wear (L). Because clustering of data could also be seen, further analysis of the variables describing barrel wear was carried out.

Based on the barrel-specific analysis presented in publication [II] the data could be divided into two groups and observations connected to two barrels were also recognized to be notably deviant. The reason for the grouping of the barrel wear values was found to be a change of barrel forcing cone construction not communicated to the people responsible for charge determination. The change of location of the ammunition in the barrel and the consequent difference in muzzle velocity and pressure values were not remarkable enough to be directly noticed from the analyzed results of charge determination test firings.

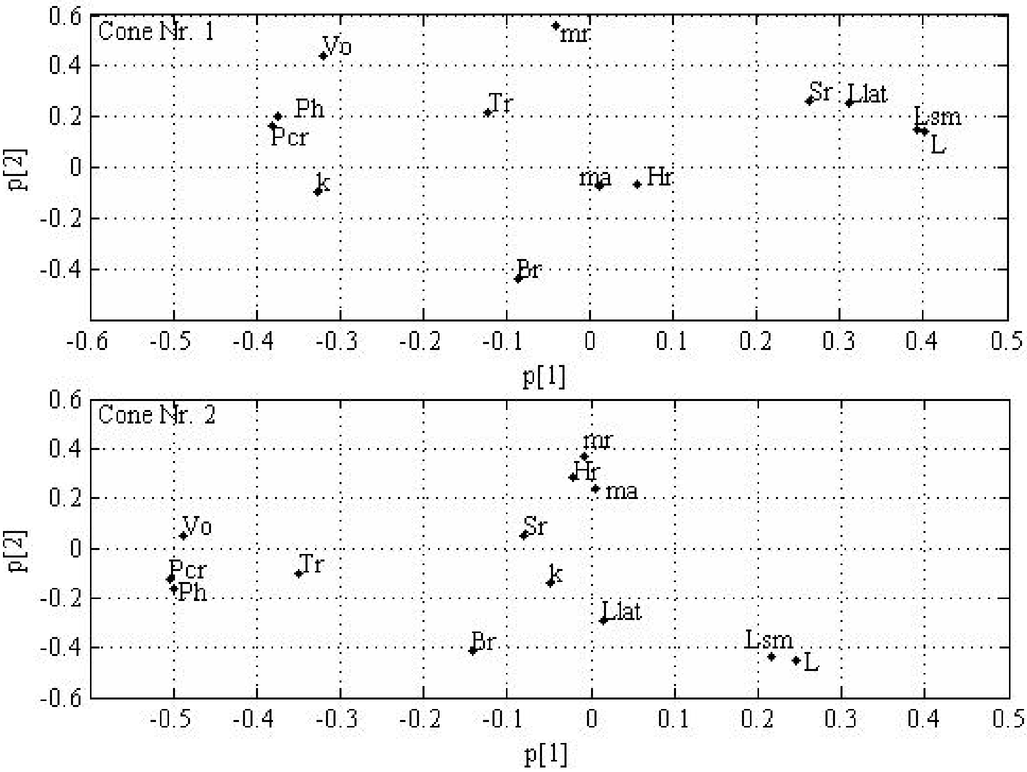

Figure 3.3. Loadings for first and second principal components for divided data sets.

The data was divided in two sets called as cones 1 and 2 on the basis of barrel forcing cone construction, and PCA was carried out for divided data sets. The loadings for the first and second principal components are presented in Figure 3.3 for cones 1 and 2. The percent variances for the five first PCs were 37%, 18%, 12%, 9% and 7% for cone 1 and correspondingly 26%, 17%, 15%, 10% and 8% for cone 2. The explanation for the lower values for cone 2 is the smaller variation in variable values in the data set. The main change if compared to Figure 3.2 is the loadings of variables located more close to each other describing barrel wear. The correlation coefficient for round number fired and barrel wear had been 0.41, but after division of the data the corresponding value was 0.98 for cone 1 and 0.92 for cone 2. This confirmed that the division of the data had been a correct decision.

3.2.2 Evaluation and diagnostics of impact of variation using PLS modeling

For both data sets two PLS models were constructed and applied for data evaluation and diagnostics. For information about variable statistics and the characteristics of the divided data sets used for PLS modeling the reader is referred to Chapter 2.1 in publication [II]. The explanatory variables for model 1 were temperature of propelling charge (T_r), relative vivacity of propellant lot (B_r), moisture content of main propellant (H_r), projectile weight (m_a), barrel wear (L) and muzzle velocity (V_0) and for model 2 T_r, weight of main propellant (m_r), B_r, H_r, m_a, L and V_0. The response variable for model 1 was m_r and for model 2 piezo-electric and crusher peak chamber pressures (P_h and P_{cr}).

The cumulative sums of variance captured by the model from the X block (ΣR^2X) and Y block (ΣR^2Y), the root mean squared errors from cross validation ($RMSEP_{CV}$) and the predictive abilities of the models from cross validation (Q^2_{CV}) with optimal number of PLS components for models 1 and 2 are presented in Table 2 in publication [III].

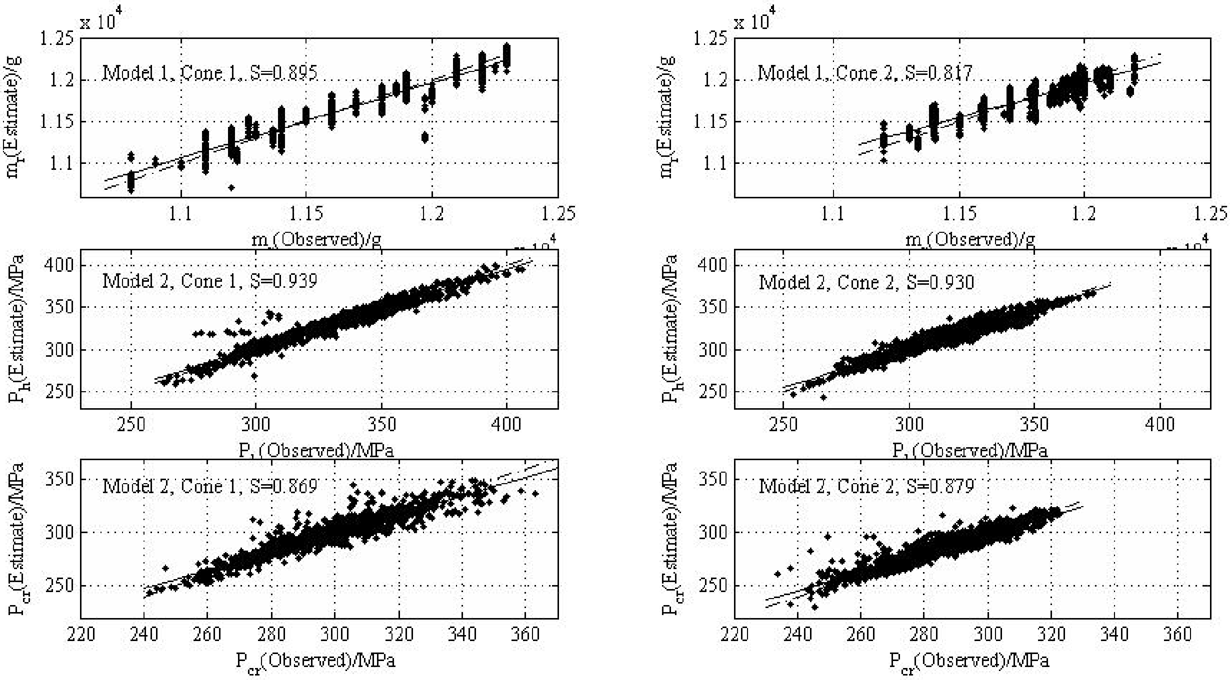

Figure 3.4. Observed values vs. estimates of response variables m_r (model 1), P_h and P_{cr} (model 2), and the fitted lines with their slopes (S) and the identity lines (-·-) for cones 1 and 2.

The observed values vs. estimates scatter diagrams for response variables weight of main propellant (m_r) and piezo-electric and crusher peak pressures (P_h and P_{cr}) for cones 1 and 2 are presented in Figure 3.4. In the estimation of m_r, P_h and P_{cr} the optimal numbers of PLS components were used.

The PLS models 1 and 2 were applied to several evaluations of the data set in hand. The targets of these evaluations, their results and conclusions are presented in Table 3.1. For the details about these evaluations the reader is referred to publication [III].

3.3 Conclusions

PCA was found to be a suitable preliminary analysis method for revealing clustering and correlations in the data studied. The PLS-models constructed for the data could be applied in the evaluation of the defects of the conventional analysis method and in the evaluation of status of produced propelling charge lots (Table 3.1).

The results of Case II revealed a need for several corrective measures in the test procedure used in the FDF for determining charge weight. Thus, during the collection of the data for this study some improvements in temperature conditioning methods of propelling charges and regulation and measurement methods of propellant moisture content had already been made. The propellant manufacturing process was also further developed to minimize lot-to-lot variation in the propellant burning properties.

The results of the principal component analyses show that there is a need to better control the stability of parameter values. In principle, the barrels to be used in the test firings have to be passed over the Ballistic Hump phases i.e. to be fired for more than about 250 rounds. The maximum allowed number of rounds fired also has to be defined for each gun type. Only nominated projectile lots may be designated to be used in charge establishment and acceptance test firings.

The results of applications of PLS models strongly stress the importance of an in-depth definition of the calibration coefficients of barrel wear, the weight of projectile and moisture content for muzzle velocity and maximum pressures in the design phases of a gun propelling charge. This has already been taken into consideration in the ongoing propelling charge design projects ordered by the FDF. The quality of test procedure for determining charge weight has also been improved by the introduction of a reference round series in the test firings combined with statistical follow-up. In addition a more systematic approach to be followed in the design phases of gun propelling charges has been introduced by the FDF and Finnish defense industry. The NATO standardization has been applied on for example in the definition of ballistic properties of the propellant [5], in the qualification of explosives [182] and in the safety and suitability testing for service (S^3) [6]. There has also been an aim at a system approach in information acquisition for a gun system including ammunition.

Table 3.1 Targets of evaluations carried out by using PLS applications, their results and conclusions.

Target of Evaluation	Results	Conclusion
The reliability of the correction factors for muzzle velocity and peak pressure used in the initial conventional analysis of the data set.	a) The correction for barrel wear should have been greater than had taken place in the conventional analysis of the results. b) Only rough estimates for correction factors could be gained by using PLS models developed.	a) The conventional analysis of the results of each uniformity test present in the cone 2 data set has been revised using more closely defined estimates of correction factors gained from the comparative ballistics and the standard value for barrel wear for cone 2. b) Test firings using designed experiments have to be carried out for the definition of accurate correction factors.
The impact of the barrel cone construction change on a) the established weights of main propellants (m_r). b) the muzzle velocities (V_0) and on the peak chamber pressures (P_h and P_{cr}) in the uniformity tests.	By using cone 2 a) established weights of main propellants were higher b) lower muzzle velocities and peak pressures were obtained in the uniformity tests than by using cone 1 (Table 4 of publication [III]).	Cone 1 barrels have been removed from service.
The scale of error of established weights of main propellants (m_r) in the data set.	The use of more worn barrels with cone 1 compared to cone 2 and the use of too low correction factor of barrel wear had mitigated the influences of above described impact of the barrel cone construction change.	Not many oversized charges could be found in cone 2 uniformity tests results.
Muzzle velocity estimation of the charge lots present in the data and comparison of the estimates with the muzzle velocity requirement.	By using data of revised conventional analysis the charge lots with greater than 5 ms^{-1} deviation from the muzzle velocity requirement could be recognized.	The user could be provided with charge lot specific expected muzzle velocity deviations where necessary.
The recognition of the propelling charge lots in the data having risk of exceeding the defined maximum permissible peak pressure for the charge type.	In this sense risky propelling charges had been produced of three high relative vivacity propellant lots.	High pressure level of risky charge lots was ensured in a test firing. The risky charge lots were sentenced to be used only for test purposes.

Based on PLS predictions and the results of an additional test firing the charge lots having peak pressures exceeding the maximum pressures could be rejected from the practice firings and be designated to be used only for test firing purposes. The user has also been provided with expected difference information in cases where muzzle velocity or the muzzle velocity distribution of a certain gun propelling charge lot has differed from the requirements. The instructions about the principles for the use of these lots and estimates of their deviations of muzzle velocity requirements have been generated and introduced in the FDF. These known differences of muzzle velocity for certain propelling charge lots was one reason for the development of the system for muzzle velocity collection in conscript field artillery practice troop firings to be discussed in Case Study III of this dissertation.

4 Case III: A surveillance system for gun propelling charges utilizing conscript practice troop firings

4.1 Introduction

The NATO standardization for monitoring the condition (and location) of ammunition during its life span, the so-called Health Monitoring of Munition (HMOM), is in its early stages. The work for HMOM has included feasibility studies on a range of sensors, microsystems based components, data communication techniques, data management systems as well as life and safety assessment methodologies and algorithms [183]. On the other hand there already exist standardized methods for monitoring and predicting the chemical stability of the gun propellants used in gun propelling charges during their life span [184-186].

One part of HMOM is the monitoring of the functional properties of the propelling charges. The main propulsion-related factors limiting the functional life of a gun propelling charge are chemical incompatibility processes, migration of surface agents and brittleness of propellant grains because of mean molar mass reduction of the nitrocellulose. There may also be damage in charges due to handling and transportation.

The following two methods to study functional life of ammunition or propelling charges were presented in the literature. The first method was developed by the Bundeswehr Technical Center 91 [187]. After artificial aging of ammunition at elevated temperatures the stabilizer content of propellants were analyzed and the dynamic vivacities of propellants and the pressure curves for test fired ammunition determined. Although the correlations between measured parameters had not been very promising a method to predict performance (i.e. maximum pressure) of 5.56, 7.62 and 9-mm ammunition stored in a hot climate in field operations was proposed. The equipment developed for propellant stabilizer content measurement in the field conditions is available for use in the application of this method [188]. A method with the same principle to study the functional life of gun propelling charges is under development in the FDF. The basis of prediction will be established in the design phase of a new gun propelling charge. The follow-up of the change of ballistic properties will take place at regular intervals during the life cycle of the propelling charges.

Bohn [189] has presented another method for predicting the usability of ammunition in field operations. Application of this method entails knowing the reaction kinetics of the nitrocellulose propellants used in propelling charges. In order to achieve this goal the stabilizer consumption and/or the molar mass decrease of nitrocellulose must be analyzed after artificial aging of studied propellant types at several elevated temperatures. The usability prediction is carried out on the basis of reaction kinetics and the documented temperature history of ammunition in field operation. The limitation of this method is that the changes in the ammunition performance are assessed solely according to the chemical aging of the propellant.

Several reasons could be seen in the FDF to develop a system to collect information of rounds fired in conscript practice troop firings. At the end of the 1990s the FDF began to seek a means of monitoring the changes of functional properties of gun propelling charges. There had also been some quality issues with some recently produced propelling charge lots as described in Case II. In addition to this the FDF had noticed the need to strengthen the follow-up of ammunition in hot climate international operations.

The aim of Case III was first to develop a system to collect information on rounds fired in conscript practice troop firings. System development has been described in publication [IV]. The second aim was to evaluate the sources of variation in the data collected by the system developed. This has been described in publication [V]. The last aim was to develop a method to assess for the fired gun propelling charge lots and zones the realized muzzle velocity deviations from the firing table values.

4.2 Results and discussion

4.2.1 System for gun propelling charges utilizing conscript practice troop firings

The surveillance system developed for gun propelling charges utilizing conscript practice troop firings comprises the collection and storage of muzzle velocity data from conscript practice field artillery troop firings by muzzle velocity radars, filing of data in the database and the statistical analysis of data collected. The sequence of the system developed is presented in Figure 4.1. For a more detailed presentation of the system developed the reader is referred to publication [IV].

The greatest challenge in the system development was to organize the measurement and storage of muzzle velocities and the information needed to trace the rounds for each round fired. The general practice in conscript practice field artillery troop firings had been the measurement of muzzle velocities of only a couple of rounds fired in order to aim the gun. This objective was not feasible before the introduction of muzzle velocity radars able to store the needed information automatically.

The Muzzle Velocity Database developed has been found to be suitable for the storage of data and for the presentation of corrected muzzle velocity data connected to selected charge types and zones, projectile types, charge lots, barrel and gun numbers as well as occasions as a function of firing date, barrel wear and the production year of charge lot. The total number of the rounds stored in the Muzzle Velocity Database representing three weapon systems is to date over 9,000.

1. Decision about ammunition combinations and gun propelling charge lots to be fired next year

2. Muzzle velocity data collection in troop firings

3. In connection with maintenance of guns
    - Downloading of radars
    - Collection of barrel wear data
    - Mailing of data to DFMC-HQ

4. Storage and processing of data in Muzzle Velocity Database

5. Further data processing

6. Feedback on the results to the user

Figure 4.1. Sequence of the surveillance system for gun propelling charges utilizing conscript practice troop firings. (Defence Forces Materiel Command Headquarters, DFMC-HQ)

4.2.2 Data set

The total data set applied in Case III comprised 7,576 muzzle velocity observations. The observations had been collected during conscript practice troop firings of 155-mm guns and high explosive projectiles with bag type propelling charges. The muzzle velocities studied had been corrected to correspond the standard values of the propelling charge temperature, weight of the projectile and barrel wear. Each muzzle velocity observation $V_{0,Lo,G,P,Z,F}$ in the data set represented a given gun propelling charge lot (Lo=1 to 29), gun number (G=1 to 46), projectile type (P=1 to 4), charge type/zone combinations (Z=1 to 6) and firing occasion (F=1 to 5).

4.2.3 Analysis of variation sources in data

The targets, methods, results and conclusions of the analyses of variation sources in the data set are presented in Table 4.1. For more detailed presentation of the analyses the reader is referred to publication [V].

4.2.4 Gun propelling charge lot and zone specific muzzle velocity data analysis

It is characteristic of the system developed that some of the observations collected have to be eliminated because of lacking or deviant information. The share of acceptable observations is strongly dependent of the standard of training and/or ability of each troop to carry out measurements during the troop firings.

During the data storage the feature of the Muzzle Velocity Database for interactive identification of records with lacking information to be eliminated and the data with minor imperfections to be completed is used. Even so, it was deemed necessary to develop a method to recognize and remove possible erroneously marked observations more effectively (most often incorrect projectile type numbers) and outliers from the muzzle velocity data. In addition, a more effective statistical tool was needed to analyze gun propelling charge lot and zone specific muzzle velocity data collected in conscript troop firings.

The solution to the above mentioned needs was a new method implemented as a function programmed by using Matlab®. This method elucidated the muzzle velocity data with four graphs and in a tabular form. For a more detailed presentation and a demonstration of method developed the reader is referred to publication [V].

Table 4.1 Objects, methods, results and conclusions of the analyses of variation sources in the data set.

Target of analysis	**Methods and Data**	**Results**	**Conclusions**
Definition of muzzle velocity difference of the first rounds in the series fired from the rest of the rounds in the series fired.	One-way ANOVA analysis The data sets were grouped to the first, the second, the third and the subsequent rounds in the series fired. 1. A total data set (7,576 rounds) 2. A charge zone 2 data set (3,888 rounds)	Only the muzzle velocity difference between the first, fourth and the subsequent rounds in the series was found to be statistically significant at the 0.05 level for the both data sets.	The variation in the muzzle velocity data can be reduced by deleting the first round in the each series fired before further analysis of data.
Suitability of the muzzle velocity data collected for the evaluation of the validity of the in the firing tables presented round combination and gun system specific muzzle velocity values.	The data was scaled by subtraction of the specific firing table muzzle velocity values from the muzzle velocity results. The results for several round combinations fired with same charge lot and zone but with different projectile types were compared.	For charge zone 2 a clear difference in scaled results between different charge/projectile combinations was detected.	There is a need to verify the specific muzzle velocity values presented in the firing tables for the studied charge zone 2.
Suitability of the muzzle velocity data for focusing the estimates of lot-to-lot, gun-to-gun and occasion-to-occasion variances.	1. Unbalanced two-way ANOVA with 95% confidence and random effects 2. Multicomparison test Charge zone 4 muzzle velocity data set consisting of 429 rounds from five charge lots fired from seven guns.	The defined estimates for standard deviation were 3.29 ms^{-1} for the gun number, 2.32 ms^{-1} for the charge lot number, 0.98 ms^{-1} for their interaction and 2.19 ms^{-1} for the remaining variability not explained by any systematic source (i. e. Error).	Statistically significant lot-to-lot and gun-to-gun differences could be found in the muzzle velocities. The fairly high variation found in charge lot-to-lot muzzle velocities most probably ensues from the quality issues discussed in Case II. Data from a higher number of firing occasions is needed for the analysis of occasion-to-occasion variances.

An example of charge zone 2 muzzle velocity data after removal of deviant results is presented in Figure 4.2.The information in these four graphs comprises the overview of the charge lot specific muzzle velocity variation in the results (Graph 1), gun-to-gun variation in the data (Graph 2), the distribution of mean centered muzzle velocities (Graph 3) and a superimposed normal density and a normal probability plot for graphical normality testing (Graph 4). The deviant results, if present, can be typically observed as outliers in Graphs 1 and 2, data not being normally distributed in Graph 3 and as Graph 4 not appearing linear.

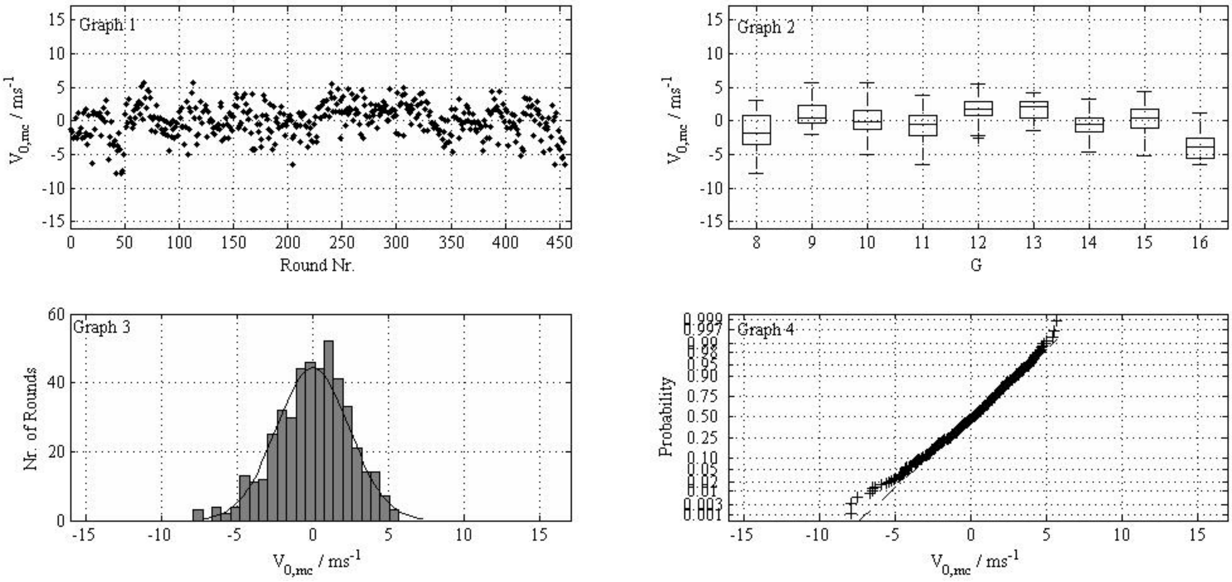

Figure 4.2. Example of Graphs 1 to 4 for evaluation of the muzzle velocity results ($V_{0,mc}$ = mean centered muzzle velocity, G = Gun number).

Based on the statistical analysis of the corrected muzzle velocities from which outliers have been removed, the muzzle velocity mean, standard deviation and their 95% confidence intervals can be presented for each studied charge lot, charge zone (and projectile type) studied. If greater deviation from the specific firing table muzzle velocity than the highest allowed is discovered, the user will be provided with charge lot and zone specific expected muzzle velocity deviations.

4.3 Conclusions

The surveillance system developed and verified enables collection of muzzle velocity data from several conscript practice field artillery troop firings occasions, several guns and the several thousand rounds fired annually. The collection of data can be carried out even in Finnish winter conditions. It has been shown that data collected by the system can be used for a variety of purposes as long as the characteristics of the data have been taken into consideration.

The variation sources in muzzle velocity data collected by the system developed have been analyzed. The conclusions of these analyses are presented in Table 4.1.

A method to eliminate deviant information from the muzzle velocity data collected by the system was developed. This method developed also includes a tool to analyze gun propelling charge lot and zone specific muzzle velocity data.

5 Assessment of the dissertation

5.1 Level of information obtainable by evaluation of gun propelling charge performance during the life cycle by statistical utilization of data collected in test and troop gun firings

The work described in this dissertation has led to several improvements in the FDF and the defense industry having a positive impact on the quality and safety of the gun propelling charges during their life cycle. The main improvements will be discussed in the following.

The output of Case I is the availability of a verified dynamic calibration method for crusher element lots. After a Handke crusher gauge measurement two peak pressure values can be presented, a value based on now available dynamic taring tables and another value based on conventional static taring tables. Dynamic Handke crusher gauge peak pressure values are close to the peak pressure values measured by the piezo-electric method at the same location of the burning chamber. From now on it will be easier to detect the deviant crusher and/or piezo-electric results on the course of test firings in cases where both pressure measurement methods are applied. The traceability of the Handke crusher gauge measurements is assured, because the peak pressure values based on static taring tables are compatible with the peak pressures for Handke crusher gauge presented earlier. The results of Case I have dispelled the discrepancy related to crusher pressure measurement.

The calibration methodology described in Case I could be applied for several types of crusher gauges, especially for the dynamic calibration of crusher elements designed for tank firings. In these firings higher peak pressures and pressure rise rates take place than in the artillery firings discussed in Case I. Such high pressure rise rates can be difficult to realize with the present NATO dynamic calibration methodology for crusher gauges, which is based on laboratory simulations and test firings.

In Case II the conventional data analysis method used in the test procedure for determining charge weight could be improved based on the reanalyses of 155-mm full charge data set by using PCA and PLS modeling as alternative methods. With more closely defined correction factors and taking into consideration the results from comparative ballistics in the test procedure for determining charge weight more reliably analyzed muzzle velocity and peak pressure results can be expected in the forthcoming charge establishment and uniformity tests. As a consequence the safety of the charge determination procedure has been improved, because now there is a minor risk of exceeding defined maximum peak pressures.

The 155-mm charge lots included in the data set expected not to fulfill the acceptance criteria could be recognized and the user provided with information of expected muzzle velocity deviations from the specific firing table values. The charge lots in the data set with safety risk exceeding defined maximum peak pressures could be designated to test purposes.

The surveillance system for gun propelling charges utilizing conscript practice troop firings described and evaluated in Case III provides an opportunity to follow up the performance of gun propelling charges at a desired point in their life cycle. The performance of charge lots with known minor quality issues especially can be monitored by using this system. Examples of these are the charge lots with possible composition changes of the propellant (e.g. migration), slightly opened cartridge covers or expected deviant muzzle velocities, like some of the 155-mm full charge lots discussed in Case II. The system also offers a new way to gain knowledge about round-to-round, charge lot-to-lot, gun-to-gun variations. The system can also be used in the follow up of the realization of the firing plans and the consumption of ammunition in troop firings.

5.2 Methodological remarks and challenges in the future

The approach of this dissertation was a statistical utilization of the results collected in test or conscript troop firings. A characteristic for all results of firings analyzed was that the firings had been organized without interface to this study. Hence the designs of experiments had not been conducted for the purposes of this study. The results of this study show that there are several ways to apply this type of data for the improvement of procedures, safety and quality in gun propelling charges.

In Case I the data set composed of peak pressures and pressure curves collected in test firings of several artillery guns could be used in the verification of the dynamic calibration model developed for Handke 28-5 5 x 7 mm cylindrical crusher element. Because there is a relatively high uncertainty in pressure measurement, only indicative information could be obtained about the effect of pressure rise time on the static crusher peak pressure values.

The calibration model developed in Case I is valid only at room temperature. However, laboratory testing facilities to extend the model to lower and higher temperatures exist. In addition to this, laboratory testing facilities allow the development of calibration models for several types of crusher gauges in the future. The Hopkinson Split Bar device is especially suitable for the definition of calibration tables for crusher gauges intended for high pressures and short pressure rise times, for example to be used in tank gun firings.

In Case II the data set was composed of the results of 155-mm charge establishment and uniformity tests. The overview of the data was obtained by using PCA and further analysis carried out by applying PLS modeling. PCA and PLS were found useful methods in the assessment of the test procedure used in the FDF for determining charge weight. A multivariate analysis approach allowed the examination of data connected to several propellant and test firings simultaneously. This approach helped to reveal elements of information which had been difficult to trace with the conventional analysis method. The last mentioned method is based on correction factors and separate analysis of data connected to each propellant lot and/or test firing.

The 155-mm PLS models developed, or analogous models to be developed for other round combinations, could be used for quality monitoring the test firing results of test procedure for determining charge weight. With this monitoring the possible deviations and trends in data or changes of parameters, i.e. a change of barrel construction, could be detected.

The construction of the data set in Case II was not optimal for multivariate analysis, because the design of experiments for this purpose had not been applied. For example, the variables temperature of propelling charge (T_r), relative vivacity of propellant lot (B_r), moisture content of main propellant (H_r), projectile weight (m_a), barrel wear (L) and weight of main propellant (m_r) did not have individual values for each observation and for part of the variables the range of variable values was quite narrow. This may have skewed the models constructed if several such variables had extreme values simultaneously. Despite these limitations the PLS models constructed were usable in the evaluation of the defects in the conventional analysis method and in the estimation of performance of the produced propelling charge lots.

The defense industry has for economical reasons proposed to stop to perform uniformity tests as a part of the test procedure for determining charge weight. Though many quality issues have been recognized and mitigated as described in Case II, there is no ground to stop the practice of firing uniformity tests because of quality and safety reasons.

The wide variation present in the experimental interior ballistic data (e.g. in the data set of Case II) should also be taken into consideration in the application of mathematical interior ballistics models. The following applications of the Monte Carlo simulation were found in the literature. Pocock and co-workers used FNGUN software to study the effect of statistical variation in gun propellant grain geometry on interior ballistic modeling. Their comparison of eccentric and concentric grains [190] and of the Monte

Carlo integration surface area simulation for a 1000 grain propellant bed [191] showed that an average non-perfect grain has a smoother regression-surface curve shape than the perfect one. When applied to a 155-mm gun system firing they found the non-perfect grain model to give a lower peak chamber pressure. Xiaobing et al. [192] studied the effect of random parameters in the initial loading conditions on the scattering of maximum pressure and muzzle velocity of a 57-mm gun. They built a Monte Carlo mathematical model on the data consisting of results for loading density, web thickness, propellant force and ignition delay measured in the proving grounds. They utilized random values sampled by the Monte-Carlo model in maximum pressure and muzzle velocity predictions carried out by a lumped parameter interior ballistics model. The resulting muzzle velocity and pressure data obeyed the normal distribution, but the calculated standard deviations were higher than in the experimental data. They found that in addition to the variables studied, several random factors such as burning regularity and engraving process had an influence on the ballistic performance.

In the FDF conscript practice troop firings some few thousand rounds are fired annually. The information on these rounds can be collected and stored by the surveillance system for gun propelling charges utilizing conscript practice troop firings described in Case III. After statistical analysis the stored data can be applied in many ways as described in Chapter 4. So far the system has been used only in army artillery field firings, but it could be extended to other branches of the armed forces having Weibel MVRS-700SC muzzle velocity radars. One additional application of this system could be the compatibility comparisons between different weapon systems from which the same round combinations are fired.

The observations collected also give information about the practices in the troop firings. One quality restriction of this system is that conscripts take care of the measurements. Much effort is needed in training and supervision of taking measurements to ensure an adequate amount of acceptable quality data. The rhythm of firing and the round combinations to be fired in conscript troop firings also ensue from the training purposes of conscripts. As a consequence there may be a small number of rounds in series for full and other high zone propelling charges and occasionally long delays between the rounds fired. Undoubtedly a better basis for statistical analysis of data collected could be achieved if the design of experiments will be applied.

The new surveillance system for gun propelling charges utilizing conscript practice troop firings enables the acquisition of information on possible performance changes, not only on the well-established gun propelling charges, but also on the products having new charge constructions and/or new propellant compositions. Information about the aging properties affecting the performance of these newcomer products at an early date after qualification testing would be valuable. In the assessment of the charge lot after muzzle velocity data collection all applicable data acquired from the acceptance records to the chemical surveillance and chemical compatibility related to each charge lot and zone should be analyzed simultaneously to gain an adequate overall conception picture of the status of the product. Data for this purpose in the future can also be obtained using the Finnish functional life prediction method for gun propelling charges as discussed in Chapter 4.1. Further study is needed before these diverse pieces of information can be systematically consolidated.

The use of the surveillance system developed could be very advantageous in hot climates. First of all the chemical aging reactions of nitrocellulose propellants are accelerated as a function of temperature. Secondly, the change in the performance of the propelling charge may elevate the maximum pressure level to be higher than that defined in context of gun propelling charge design. When these considerations are combined with the positive temperature dependence on pressure for traditional propellants, there is a risk of exceeding Cannon PMP. The surveillance system developed already includes the feature of main propellants temperature value input and storage in the memory of the muzzle velocity radar during the troop firings. Moreover, the gun propelling charge temperature should be monitored during storage and transportation by using temperature data loggers. Here too, the availability of all relevant chemical data should be ensured.

The further development of application of strain gauge measurement in pressure determination during interior ballistic phases [161] could provide a capability to measure and store not only muzzle velocities but also peak pressures or even pressure curves in troop firings. This would yield remarkable improvements in the system described in Case III and in the studies of the performance of propelling charge lots approaching the final stage of their life cycle. The higher propelling charge lot specific peak pressure values detected, if compared to peak pressures reported after propelling charge lot uniformity tests, would strongly indicate a change in the ballistic properties of the propelling charge lot in question.

6 Concluding remarks

The objective of this dissertation was to develop methods to improve the safety and quality of gun propelling charges during their life cycle. The main approach was a statistical utilization of the results collected in artillery gun test and conscript practice troop firings. It was a characteristic of all the firing results analyzed that the firings had been organized independently of this study.

The interior ballistics branch has to adjust to the new demands for weapon systems. The literature survey suggests that the main trends in recent interior ballistics research are the development of new more energetic but less sensitive and toxic gun propellant compositions and new high loading density grain configurations and propelling charge constructions. In order to develop more effective propelling charge ignition methods and to avoid pressure wave formation, better knowledge of ignition event was obtained. In particular, the last mentioned and also the research on heat transfer in the gun barrel and the studies on barrel wear were facilitated by the rapid and diverse progress of mathematical modeling. The prerequisites of success are an understanding of the interdisciplinary nature of this branch and the practice of skillful system engineering.

Interior ballistic test firings are carried out for various reasons in the several stages during the life cycle of the gun propelling charge. It is necessary to be able to measure the correct chamber pressure during the ignition and combustion of gun propellants in all interior ballistics firings. In the worst case inaccurate pressure measurements may lead to a barrel break and a danger to the gun crew, due to the unexpectedly high pressure produced by a gun propelling charge. The new laboratory calibration method developed and validated for crusher pressure gauges improves the reliability of the combustion chamber pressure measurement in test firings [I].

The charge establishment test firings are carried out in the gun propelling charge design and production phases and the uniformity firings in the production phase. The results of uniformity test firings form a baseline for the performance for the usable life time of a gun propelling charge lot. Quality defects were found in several recently produced 155-mm full gun propelling charge lots. By applying multivariate analysis methods principal component analysis (PCA) and partial least squares (PLS) modeling the reasons for the poor quality of the gun propelling charges studied were ascertained and the test procedure used for determining gun propelling charge weight was improved [II-III]. In addition the assessment for the propelling charge lots studied was given.

The knowledge of the performance of the gun propelling charges in operational use can be extended with a new capability to collect and statistically analyze muzzle velocity values realized in troop firings [IV-V]. This new surveillance system for gun propelling charges utilizing conscript practice troop firings enables information acquisition of possible performance changes, not only of well-established gun propelling charges, but also of the products having new charge constructions and/or new propellant compositions. Besides the aforementioned, other feasible applications of the muzzle velocity data collected by the system developed have been presented in this study.

The application of the results and of the new methodologies presented in this dissertation has led to several improvements in the Finnish Defence Forces and in the defense industry. These improvements have had a positive impact on the performance, quality and safety of the gun propelling charges during their life cycle.

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