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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 172

Fluid Dynamics Aspects of Internal Ballistics

NORTH ATLANTIC TREATY ORGANIZATION

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.172

FLUID DYNAMICS ASPECTS OF INTERNAL BALLISTICS

Report of the Fluid Dynamics Panel

Working Group 05

This Advisory Report was prepared at the request of the Fluid Dynamics Panel of AGARD.

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Chapter 1

INTRODUCTION

The marked advances achieved in the last few years in fluid dynamics can be related to the development of increasingly powerful computers of easy manipulation, new numerical methods, modern test facilities and improved data recording and processing systems. Thus an increasing amount of reliable information has become available. The state of progress reached has opened the way for improved modeling of turbulent events and allowed more and more complex problems to be investigated.

For the same reason a marked step forward has simultaneously been made in the field of interior ballistics. In particular, important advances are being achieved in improving the methods of analysing and predicting fluid flows in interior ballistics. At the same time new techniques are being developed in the field of propulsion (especially as far as liquid propellants are concerned) which give rise to new and specific problems.

It was therefore considered worth while to verify the extent to which the experts in interior ballistics could take advantage of the progress recently achieved, both theoretically and experimentally, in fluid dynamics. Toward this end the AGARD Fluid Dynamics Panel decided to create a Working Group (AGARD FDP/WG.05) with experts in interior ballistics from six NATO countries (Belgium, France, Germany, Great Britain, Netherlands, and the United States).

This Working Group was active for 30 months. The composition of the Group determined the way chosen by the members to fulfil the assigned task. Efforts were made to work out a synthesis of the know-how attained in the field of interior ballistics in the six NATO countries concerned, the emphasis thereby being placed on the fluid dynamic aspects. Furthermore, the areas are underlined in which advances still remain to be achieved. In order to achieve the assigned mission, four plenary meetings of the Working Group were held. Moreover, an active and repeated exchange of information was conducted by writing. A widespread inquiry was launched by the Group members in their countries in order to provide information about the basic research work conducted in the common field of interest. The results of the inquiry were gathered in form of data sheets made available to all members of the Workging Group by mutual exchange. If necessary, additional information was requested for working out the written contributions to the final report.

In order to accomplish its mission in an optimal way, the Working Group consulted experts in fluid dynamics (Prof. Broadbent, IGA Carriere, Prof. Krause). Finally the authors of various computer codes were contacted in order to get insight into the objectives and contents of these codes.

The present report is organized as follows:

One chapter devoted to the interior ballistics cycle including the presentation of different models and computer codes used in interior ballistics. An example of application is given. Furthermore the experimental methods and associated theories are described, which allow the foregoing models to be validated. These methods and theories also yield indispensable input data and allow to verification of the computed results.

One chapter deals with the gaseous outflow from tube launchers.

One chapter is concerned with the physical and thermodynamic characteristics of propellant gases.

One chapter is devoted to a few specific problems encountered in interior ballistics (liquid propellants, behaviour of anti-erosive additives, behaviour of solid propellants at high pressures).

Much work has been done in the field of interior ballistics. Experts in fluid mechanics will note the smooth integration of recent developments achieved in their region of interest into the somewhat more specific domain of interior ballistics. This is not surprising because a close relationship exists between the armed forces research laboratories and the universities and aeronautical research centres as well (DFVLR, RAE, ONERA). In spite of the efforts made, however, there are domains in which the results achieved call for further improvement (gas circulation at the level of the combustion chamber or in the vicinity of the base of the projectile, boundary layer and interaction with the tube wall, gases escaping at the level of the projectile) or in which results are still completely lacking (physical characteristics of the combustion gases at high pressures).

Although the authors of the various contributions to the final report aimed at emphasizing the fluid dynamic aspects of the problem to be investigated, it was not possible (and even not wished) to pass over the phenomena encountered in other branches of science (energetics, mechanics of solids). As a matter of fact the description of the interior ballistic cycle inevitably involves all the aforementioned branches of science, the influence of each branch thereby being dependent, of course, on the phase of the cycle in which the particular phenomenon under investigation is being treated.

Chapter 2

THE INTERIOR BALLISTIC CYCLE

2.0 INTRODUCTION

The interior ballistic cycle for guns involves a complex interplay of physical and chemical processes. Classical pictures of the interior ballistic cycle typically involve its division into several distinct phases, including ignition of the propellant, combustion both prior to and during projectile motion, gas expansion and projectile motion after propellant burnout, and venting of gases from the tube after projectile exit. In the past, the assumptions of uniform ignition of the entire propellant bed and a space-averaged thermodynamic treatment of propellant gas and particles have been invoked to facilitate the generation of computerized models capable of providing a numerical description of the pressure-time-travel relationship in guns. Consideration of fluid dynamic processes has been most often limited to the super-imposition of a simplified pressure gradient associated with motion of the projectile on the lumped-parameter, thermodynamic solution, solely for the purpose of providing a more reasonable description of breech and projectile-base pressures.

In actual practice, however, this decoupling of the sequence of events occurring during the interior ballistic cycle may be far from correct. Fluid dynamic processes accompanying the initial propagation of the flame front through the propellant charge may exhibit significant impact on subsequent phases of the overall cycle. Resistance to gas flow offered by a packed bed of granular propellant may result in local pressure gradients capable of leading to substantial grain motion, as well as a traveling longitudinal pressure wave which may persist long after flamespread is complete. Equally complex are details of the chemical-reacting, transient boundary layer at the tube wall which governs those processes leading to erosion of the bore surface. These and many more features of fluid dynamic processes in the gun tube lie outside the scope of the classical picture of gun interior ballistics.

In Section 2.1 of this chapter, we provide first a description of current efforts being conducted in NATO countries to develop models which specifically address a phenomenologically more complete picture of the fluid dynamics of the gun interior ballistic cycle. Section 2.2 then offers further information on supporting theory and measurement techniques for characterization of specific ignition and combustion processes, heat transfer to the tube, and various multiphase flow parameters.

2.1 INTERIOR BALLISTIC MODELS

2.1.1 Inputs to Section 2.1

Fourteen inputs from four NATO countries were received in response to the inquiry for information on theoretical studies of the fluid dynamic aspects of the interior ballistics of guns. A listing of contributors is included as Appendix I to this chapter. The same four countries – France, Germany, the United Kingdom, and the United States – presented information on many of these efforts in considerably more detail at an AGARD sponsored workshop on the subject conducted on 22–24 April 1980, at the Royal Military College of Science, Shrivenham, England. A listing of workshop participants is included as Appendix II. The bulk of the information assembled in this chapter is based on personal communications with these individuals.

While it can be assumed that these inputs do not cover all activities in this field ongoing in NATO countries, it is hoped that the summary provided in this chapter will acquaint the reader with their general scope, as well as providing some details of what are perhaps the more advanced modeling efforts. Specific information will include motivation for work, physical scope of the models, status of ongoing efforts, and existing capabilities. Details of numerical schemes and computational techniques applied by the various investigators are outside the scope of this document, though brief comments on this area will be made. It should also be emphasized that a considerable body of closely related information on ignition and combustion processes, tube outflow, and associated experimental ballistic techniques is found elsewhere in this volume.

2.1.2 Summary of Models: Physical Scope, Capabilities, and Planned Improvements

2.1.2.1 France

Interior ballistic modeling efforts in France are chiefly motivated by the search for increased muzzle velocities for higher performance guns. In addtion to classical lumped-parameter (thermodynamic) interior ballistic models, existing capabilities include, jointly with the Germans at the Franco-German Institute for Research at Saint-Louis, France (ISL), a one-dimensional, single-phase flow model and a one-dimensional, simplified two-phase flow model originally developed at the Defense Research Establishement, Valcartier, Canada (DREV). Both models assume uniform ignition of the propellant bed, a Noble-Abel equation of state for the gas, a pressure-dependent burning rate law, and a one-dimensional with area change treatment of flow. Viscosity and heat transfer in the fluid are ignored. In the single-phase model, the gas and solid phases are assumed to constitute a locally homogeneous fluid. Numerical solutions are effected in Lagrangian coordinates using the method of characteristics. In the two-phase model, the solid-phase velocity is assumed to be related locally to the gas-phase velocity via a proportionally constant k, where $k = c_1 z^{c_2}$, z is the fraction of propellant burned, and c_1 and c_2 are adjustable constants. For this representation, a finite-difference scheme in Eulerian coordinates is applied. A.Carriere, K.Hoog, and H.Krauth of ISL report adaptation of these models for treatment of composite propelling charges and multi-state guns, with a further extension planned for the traveling-charge problem. Three References, 2-1 to 2-3, to their work are provided.

At the Société Nationale des Poudres et Explosifs, Centre de Recherche du Bouchet (SNPE-CRB), an effort is now underway, administered by the Service Technique des Poudres et Explosifs (STPE), to develop a phenomenologically more complete one-dimensional, two-phase flow model which includes flamespread through the propellant bed. M.Dervaux and C.Cuche of SNPE report that their model, based largely on US work described later in this chapter, assumes the gas and solid phases to be coupled by heat transfer, interphase drag, and combustion. Other assumptions include an inviscid, non-turbulent, non-conducting gas, a Noble-Abel gas equation of state, an incompressible solid phase with intergranular stress in excess of the gas pressure dependent on bed porosity, a surface-temperature ignition criterion for the propellant grains, a pressure-dependent burning rate law, and a one-dimensional with area change treatment of flow. The igniter is modeled as a predetermined source of energetic gases. This model has been coded for numerical solution using the explicit, two-step, finite-difference scheme of MacCormack for interior points and a one-sided differencing scheme accorded to Warming and Beam at the boundaries. Debugging is still underway and application of this code to real interior ballistic problems is yet extremely limited. Eventually, this code will be extended to include a two-dimensional, axisymmetric representation of flow and an explicit recognition of igniter functioning. Treatment of multiple-increment, bagged charges will also be addressed.

A related experimental/theoretical effort is being conducted by the Direction Technique des Armements Terrestres (DTAT) at the Etablissement Technique de Bourges-Groupement Industrial des Armements Terrestres (ETBS-GIAT). Objectives of this work are to include thermal losses in available interior ballistics models for improved predictions of performance, and to apply the results of calculations concerning the thermal transfer to the study of gun tube erosion and cookoff. Calorimetric techniques have been employed to determine the amount of heat transferred to the gun tube, with temperature measurements being taken at depths of several tens of millimeters along the tube wall using ISL-type thermocouples. Numerical simulation of heat transfer processes is currently underway, with convective heat transfer to the tube considered by reference to the data of theoretical, one-dimensional single-phase flow. Conduction within the gun tube is processed using a simple numerical method, known as the Dusinbère method, modified for cylindrical geometry. Calculated thermal losses are on the order of 5 to 8% for the first shot in a 20-mm cannon. Application of the model to analysis of barrel heating during multiple firings is planned. Three References, 2-4 to 2-6, are indicated for the work described above. Additional discussion on heat transfer to the gun tube is provided in Section 2.2.3.

2.1.2.2 Germany

In addition to joint capabilities previously described to be operational at the ISL, a number of other German models treating the gas dynamics of the interior ballistic cycle were reported.

A one-dimensional, single-phase model for treatment of the post-combustion, expansion phase has been developed by C.Heinz of RWTH Aachen, Germany and D.Hensel of ISL (Ref.2-7). Solutions are provided for an ideal, isentropic gas in Lagrangian coordinates with an iterative solution technique using special series.

Another one-dimensional, single-phase model has been developed by R.Heiser at the Ernst-Mach-Institute, Abteilung fur Ballistik (EMI-AFB), Weil, Germany. This model treats expansion of an ideal gas from a fixed bed of burning propellant. Numerical solution is based on the method of characteristics and is reported to have been applied to the differential equations expressed either in a hodographic (Ref.2-8) or physical plane (Ref.2-9).

Yet another operational modeling capability exists at Diehl, where work initiated by M.Dürschner and carried forward by Stein and Thurner has resulted in the development of a one-dimensional, two-phase flow interior ballistic model which includes treatment of flamespread through the propellant bed. Similar in physical scope to the model under development at SNPE, this model addresses the fluid dynamics of an inviscid, non-conducting gas coupled to an incompressible solid phase by heat transfer, interphase drag, and combustion. Other features include a virial equation of state for the gas, a propellant surface-temperature ignition criterion which depends locally on the relative velocity between the phases, and a temperature-dependent description of the specific heat of propellant gases. Empirical descriptions for interphase drag, heat transfer, and intergranular stress also differ somewhat from those used by SNPE. A detailed comparison of the balance equations has not been made. Numerical solutions are provided using a two-step, Lax-Wendroff finite-difference scheme, both at interior points and at the boundaries. The code is currently run separately for flamespread and post-flamespread (expansion) processes, allowing manual “optimization” of grid density and time steps. This code is charge-design oriented and application is typically made to such problems as the detailed description of down-bore pressures in a high-performance tank gun. Results have been obtained for 27-mm and 120-mm gun configurations. Two references are provided as background for this effort (Refs 2-10, 2-11).

Finally, a two-dimensional, single-phase description of the flow inside a gun tube has been developed jointly by Heiser of EMI-AFB and Hensel of ISL. This model provides a complete Navier-Stokes treatment (with velocity and heat conduction) of axisymmetric, laminar or turbulent flow in a Noble-Abel gas. The numerical solution makes use of an explicit, MacCormack finite-difference scheme with time splitting in the interior, an implicit, Briley-McDonald scheme at the base, and an explicit MacCormack scheme upwind. The code is operational and has been applied to various small-caliber weapons (e.g., 20 mm), providing solutions to the problem in which the propellant is assumed to be all burnt prior to projectile motion. Interest has centered on providing a description of the formation of the boundary layer at the tube wall and examining its influence on heat transfer leading to gun barrel erosion. Planned efforts call for extension to the two-phase problem. Two references on this work were provided (Refs 2-12, 2-13).

It should be mentioned also that local-flow solutions to the steady, laminar boundary-layer problem, both for incompressible and compressible fluids, have been provided by Heinz and his coworkers at RWTH Aachen.

2.1.2.3 United Kingdom

Several modeling efforts are underway at the Royal Military College of Science, Shrivenham, England. G.Pagan of the Mathematics and Ballistics Department has developed a more general solution to the Lagrange problem, assuming the gas density to be a separable function of space and time. Other assumptions include all propellant burnt at zero time, an ideal gas equation of state, uniform cross-sectional area, and no bore resistance. The code will be used for studying the effects of heat loss on muzzle velocity and for assistance in the validation of more complex, hydrodynamic models.

One such two-phase flow model is under development by A.Crowley, also at the Royal Military College of Science. Referred to as the ABC code, this model is very similar in physical scope to those of Dervaux and Cuche of France and Stein of Germany. Again, a one-dimensional with area change treatment of two-phase flow (inviscid gas) in a gun tube, this model assumes a Noble-Abel equation of state for the gas, an incompressible solid phase, a surface-temperature ignition criterion, a pressure-dependent burning rate law, and an uncoupled description of igniter functioning (i.e., predetermined igniter venting rate). Treatment of intergranular stress in excess of the gas pressure is not included at this time, nor is heat transfer between the gas and solid phases. Rather, flamespreading is driven by assuming the propellant surface temperature to equal the local gas temperture until the ignition criterion is met. Numerical solutions are provided by applying a two-step, Lax-Wendroff finite-difference scheme, both for interior points and at the boundaries. This code is still in the development stage, and relaxation of some of the existing assumptions is planned, including eventual extension to include a fully two-dimensional representation of flow.

2.1.2.4 United States

During the past decade, a number of efforts have been undertaken in the United States to model flamespread and combustion in a mobile, granular propellant bed. Motivated largely by problems experienced with pressure waves in medium and large-caliber guns, this work has included the efforts of government laboratories, private contractors, and universities. Several representative efforts, currently active and funded, are described in this document. References for related work are also given.

One of the most used two-phase flow codes in the United States is known as the NOVA code. Developed by P.Gough of Paul Gough Associates in conjunction with A.Horst and later F.Robbins at the Naval Ordnance Station, Indian Head, MD, NOVA is a quasi-one-dimensional, two-phase flow model of the gun interior ballistic cycle, similar again in physical scope to those models previously described of Dervaux and Cuche, Stein, and Crowley. The balance equations describe the evolution of averages to flow properties accompanying changes in mass, momentum, and energy arising out of interactions associated with combustion, interphase drag, and heat transfer. Constitutive laws include a Noble-Abel equation of state for the gas and an incompressible solid phase. Compaction of an aggregate of grains, however, is allowed, with granular stresses in excess of ambient gas pressure being taken to be dependent on porosity and in accord with steady-state measurements.

Again, macroscopic diffusion is neglected, boundary-layer phenomena associated with interphase drag, heat transfer, and combustion being assumed to act locally within each macroscopic control volume and resolved by reference to empirical correlations. Interphase drag is represented by reference to the steady-state correlations of Ergun and Andersson for fixed and fluidized beds, respectively. Interphase heat transfer is described similarly according to Denton or Gelperin-Einstein. Functioning of the igniter is included by specifying a predetermined mass-injection rates as a function of position and time. Flamespreading then follows from axial convection, with grain surface temperature deduced from the heat transfer correlation and the unsteady, heat-conduction equation, and ignition based on a surface-temperature criterion. In addition, axial internal boundaries defined by discontinuities in porosity (as between the propellant bed and regions on axial ullage, or unfilled space) are treated explicitly, and the forward external boundary reflects the inertial and compactibility characteristics of any inert packaging elements present between the propellant bed and the base of the projectile. Solutions are obtained using an explicit finite-difference scheme based on the method of MacCormack for points in the interior and a modified method of characteristics at internal and external boundaries. Extremely good agreement between theory and experiment has been achieved using this code for simulation of pressure-wave phenomena in several US Navy case guns, though similar agreement for bagged charge artillery is apparently limited by the quasi-one-dimensional approximation. NOVA is operational at several US government facilities, and formalized documentation of a standardized version is undergoing publication at the Naval Ordnance Station, Indian Head, MD. Several references describing NOVA and its application are listed in References 2-14 to 2-17.

The failure of NOVA to treat adequately bagged-charge artillery has been attributed, at least in part, to the complexity of the interface between charge and chamber and the ill-characterized impedances to gas and solid-phase flows offered by the bag and other parasitic components – both outside the scope of a one-dimensional representation. In response to this shortcoming, Gough has undertaken to develop a fully two-dimensional code which recognizes the presence of axial and annular regions of ullage external to the bag, as well as embedding the flow inhibition associated with the non-energetic charge components as physical boundary conditions linking the various regions of flow. This work has been funded by the US Army Ballistic Research Laboratory at Aberdeen Proving Ground, MD, under the direction initially of C.Nelson and later of A.Horst.

While this code, to be known as TDNOVA, is not yet fully operational, an interim quasi-two-dimensional model (QTDNOVA) has been coded and is operational at BRL. This treatment involves the decomposition of the gun chamber into four regions: namely, the contents of the bag, ullage to the front and rear of the bag, and annular ullage external to the sidewall of the bag. Two-phase flow in the bag is treated just as in NOVA except for a time-dependence of the cross-sectional area of the bag, a consequence of radial motion of the bag and the influence of radial mass transfer. Annular ullage is represented as quasi-one-dimensional, single-phase inviscid flow, while regions of axial ullage receive a lumped-parameter representation. Treating the bag and annular ullage as disjoint but coupled regions of one-dimensional flow allows for the recognition of early-time flow of igniter gases and combustion products external to the bag, altering the flame propagation path and, perhaps, equilibrating pressures longitudinally throughout the chamber. Solutions for a 155-mm howitzer calculation suggest the sensitivity of these processes to the persistence of annular ullage as influenced by bag permeability and strength. One reference is provided on this effort (Ref.2-18).

A second major development effort has been conducted over nearly the past decade at Calspan Corporation, Buffalo, NY, by E.Fisher and his co-workers. Under direction and funding first from the Quality Assurance Directorate of Picatinny Arsenal (now ARRADCOM), Dover, NJ, and more recently from the Ballistic Research Laboratory, Fisher has developed a one-dimensional, two-phase flow code again similar in physical scope to those described by Dervaux, Stein, Crowley, and Gough. Like many of the previously described codes, assumptions include a Noble-Abel equation of state for the gas, an incompressible solid phase, a surface-temperature ignition criterion, and a pressure-dependent burning rate law. Empirical correlations describing interphase drag and heat transfer are somewhat different, however, as is the representation of intergranular stress as a function of porosity. Viscous and heat transfer losses at the chamber wall are also considered.

A multi-one-dimensional grid option similar to that of Gough's quasi-2-D code exists, but with the additional capability of modeling flamespread in the igniter center-core used in artillery charges. An option for treatment of propellant grain fracture caused by impact against the projectile base or excessive intergranular stress levels has also been developed. Because of differences in the size of propellant grains and gas molecules, Fisher does not view the two phases as homogeneous, interpenetrating continua. Consequently, he provides numerical solutions by integration of the balance equations in a gas-phase finite-difference network using a modified Lax scheme, updating the solid-phase mass and momentum balance equations without use of a formal finite-difference scheme. The Calspan code has been used both for study of propellant production control problems and simulation of pressure waves in artillery. The code is operational at several US Army installations, though some streamlining of coding is currently underway under contract to BRL. Two recent references describing this work are provided (Refs 2-19, 2-20).

Other US investigators who have been actively involved over recent years in modeling of flamespread phenomena in the gun environment have included K.Kuo of Pennsylvania State University and H.Krier of the University of Illinois. Kuo's work in this area has concentrated mostly on small arms (ball propellant) flamespread phenomena, and his efforts have included considerable experimentation to characterize such features as flow resistance and bed rheology for ball propellants. Three references to his work are provided (Refs 2-21–2-23). Krier's work initially was quite similar in physical scope to that of Gough and Fisher, though his recent efforts have focused more on the deflagration-to-detonation (DDT) problem associated with high-solids-loaded, high-energy rocket propellants. Two references on his gun-modeling work have been listed (Refs 2-24, 2-25).

Several recent interior ballistics modeling efforts in the United States have been motivated by interest in what are believed to be largely post-flamespread phenomena. Barrel-erosion problems experienced with high-performance tank and artillery systems have led to two Army-sponsored programs, at least portions of which address the development of two-phase flow models capable of treating unsteady boundary-layer phenomena in the gun tube.

H.McDonald of Scientific Research Assciates, Glastenbury, Connecticut, in conjunction with N.Banks of ARRADCOM's Ballistic Research Laboratory, has developed a two-dimensional model known as ALPHA. Like Heiser and Hensel's model, the full Navier-Stokes equations are solved for an axisymmetric, time-dependent, compressible, viscous flow; however, extensions for treatment of turbulence and two-phase flow have been incorporated. Many of the physical submodels (e.g., interphase drag and heat transfer, propellant bed rheology) have been adopted from NOVA, though at this time ALPHA addresses only post-flamespread processes. A Noble-Abel equation of state for the gas and a pressure-dependent burning rate law are also employed. A split-linear-block-implicit finite-difference scheme is employed to provide numerical solutions. This code has recently been implemented at BRL where validation studies are underway. Turbulence modeling is being tested in the single-phase mode using a turbulence kinetic-energy equation. Current efforts also include extension of the scope of the model back in time to include flamespreading, development of a dynamic grid-transformation scheme for accurate and efficient treatment of strong flow gradients, and development of a scheme for efficient use of mass storage. While originally motivated by the problem of heat transfer to the tube, ALPHA may well be applied to a much broader class of problems once flamespreading has been successfully implemented. One reference has been provided (Ref.2-26).

Relevant to the same problem, the Army Research Office and ARRADCOM have jointly funded an effort at Lawrence Livermore Laboratories, California to determine the dominant mechanisms of hot gas flow erosion of exposed solid materials (i.e., the gun-bore surface). Included in this program are several tasks to model the unsteady, turbulent, chemically reactive, multicomponent boundary layer. A.Buckingham is simulating the influence of particulate matter (e.g., propellant or additives) on the erosive transport processes in a turbulent, reactive boundary layer (Ref.2-27). S.Kang and J.Levatin are developing a time-dependent description of the flow field in the boundary layer, including reactive species, turbulence, and propellant additives, and taking into account the conditions of the unsteady core flow and heat transfer at the bore surface (Ref. 2-28). The eventual level of coupling between these models and a master interior ballistics code including flamespread is unclear at this time.

2.1.2.5 Other Capabilities

A.Schenk of the Prins Maurits Laboratory (PML), the Netherlands, reports that the Calspan code is operational at his facility, where it is employed in response to a variety of charge-design problems. Other such capabilities no doubt exist in various NATO countries, unknown to the authors of this chapter at the time of its writing.

2.1.3 Related Inputs

A variety of work is being conducted in the NATO countries which does not fall into the general category of two-phase flow, interior ballistic model development, but which, neverthelesss, contributes significantly to the overall technology area. A summary of inputs provided on such work is included in this section.

2.1.3.1 Ignition and Combustion Submodel

D.Kooker of ARRADCOM's Ballistic Research Laboratory is pursuing detailed modeling of solid-propellant ignition and transient combustion as a necessary input or "building block" in the total interior ballistics model. His efforts have been directed toward two parallel studies.

Since the gas-phase flame region may dominate the ignition process as well as transient burning-rate adjustments, one study considers a mixture of reactive gases in a closed chamber and analyzes their behavior near the flammability limit and during transient flame propagation. This is done with a numerical solution of the compressible, time-dependent, Navier-Stokes equations for a viscous, heat-conducting, multispecies, chemically-reacting flow. The solution technique is based on the linearized block-implicit method, with the chemical production-rate terms treated separately with a "stiff" integrator. Without the benefit of adjustable constants, the predicted flammability limit for an ozone/oxygen mixture at atmospheric pressure agrees with the experimental data of Streng and Grosse. Predictions for a transient laminar flame in the closed chamber indicate oscillatory flame propagation and pronounced acceleration effects. Confined combustion appears inherently oscillatory.

The second study analyzes the behavior of an end-burning solid propellant grain confined in a closed chamber when the usual assumption of propellant incompressibility is removed. The mechanical properties (stress-strain law, fracture, etc.) of the unburned propellant will govern how the solid adjusts to the rapidly-increasing pressure field created by the confined combustion. In progress is a solid mechanics model which incorporates the time-dependent numerical solution of the equations conserving mass, momentum, and energy in a nonlinear, thermoviscoelastic solid undergoing closed chamber combustion.

Four references (Refs 2-29 – 2.32) are included for Kooker's work.

2.1.3.2 Special Problem: Blanks

S.Goldstein of ARRADCOM's Fire Control and Small Caliber Weapon Systems Laboratory, US Army, has an ongoing effort on the interior ballistic modeling of blank ammunition. The objective of this work is to develop a mathematical model and computer program which will be capable of simulating the combustion, two-phase flow and weapon-cycling kinematics related to blank ammunition. Both recoil-operated and gas-operated systems will be considered. This study is intended to result in a design tool for developing ammunition to be used for tactical training of infantry and armor personnel.

Experimental data has been obtained for Cal. .50 and 7.62 mm weapon systems. These data include information on the pressure versus time at different locations in the chamber, barrel, and blank firing attachment (BFA). From this information it is possible to trace the formation and trajectories of different compression waves and shock waves within the barrel.

For the Cal. .50 system studies, a model has been developed which consists essentially of two parts. First, a lumped-parameter treatment is made of the quasi-steady combustion of rolled ball propellant in the cartridge case and two-phase flow out the case mouth. The solution to this phase supplies the initial and boundary conditions for analysis of the ensuing non-steady flow period. A shock wave, contact surface, and expansion wave are created when the mouth of the blank cartridge opens. The flow of gas out the muzzle and pressure buildup in the BFA during the period of nonsteady flow are calculated. This information is then used to determine the formation of the reverse shock wave and the motion of the bolt and barrel. Future work may include a more detailed analysis of heat transfer and shock-wave interaction. Five references (Refs 2-33 – 2.37) are offered on this and related efforts.

2.1.3.3 Special Problem: Liquid Propellant Gun

Interior ballistic modeling for liquid propellant guns is being pursued in France by the Direction des Recherches, Etudes et Techniques (DRET), with investigations being carried out by SNPE-CRB. The objective of their work is to prepare an interior ballistic model for guns which use hypergolic bipropellants in order to carry out parametric studies at the lowest possible costs.

A one-dimensional approach based on a simple physical model relating to the laws of combustion and droplet formation has been devised. The numerical method used combines the method of finite differences for points in the interior with the method of characteristics at the breech and of the base of the projectile. This method has been prepared assuming the separation of the phenomena of propellant injection and combustion, though future plans include coupling of these processes.

Further discussion of liquid propellant combustion is included in Section 5.1.

2.1.3.4 General Study

An interior ballistic modeling effort of a general nature, is being pursued by R.Powers, Air Force Armament Laboratory, Eglin Air Force Base, Florida. The objective of this work is oriented toward conducting the analytic and experimental research required to provide the necessary interior ballistic design data for the next generation of very high velocity aircraft cannon. The program is broad in scope and has several independent facets. These include evaluation of improved high-energy propellants, muzzle-flash and heat-transfer experimentation, and the mathematical modeling of telescoped ammunition.

Extensive experimental gun firings are being conducted on telescoped 25-mm ammunition to refine a preliminary interior ballistic mathematical model. Non-contact radiometry is being utilized to determine the primary and secondary flame temperatures of muzzle flash. In-bore gas temperatures are being determined with microsecond-response surface thermocouples. The mechanics of plastic rotating-band engraving during acceleration is being studied. Also, propellant combustion products will be sampled during firings and analyzed with a time-of-flight mass spectrometer. To date, a comprehensive propellant morphology study utilizing a scanning electron microscope has been completed, muzzle-flash emissivities and temperatures have been determined, and nitramine propellant, ignition-mechanisms studies are underway.

2.1.4 Recapitulation

At least four NATO countries have developed or are developing their own numerical models for treatment of the fluid dynamic processes of the interior ballistic cycle. One-dimensional, two-phase flow models including flamespread exist at SNPE in France, Deihl in Germany, the Royal Military College of Science in England, and various contractors and government facilities in the United States. Of these, the French and UK models are reported to be still in a developmental status, while the German model at Diehl and the US NOVA and Calspan codes are operational and routinely used for charge-design problems. Even the operational models, however, undergo continual refinement. In addition, the Calspan code has been implemented for use in the Netherlands. In all cases, extension to a two-dimensional, axisymmetric-flow representation is planned, though actual pursuit of this goal is of yet underway only by Gough in the US.

A second class of models, addressing the description of flow in the unsteady boundary layer and involving solution to the full Navier-Stokes equations, is being pursued in Germany, France, and the United States. At both the EMI in Germany and the ISL in France, a two-dimensional, single phase, viscid flow model is operational, while the SRA/BRL effort in the US has resulted in a two-dimensional, two-phase (post-flamespread, viscid, turbulent) flow model. Ultimate extension of both models is planned to provide a two-dimensional, two-phase description of turbulent, chemically reacting flow in the gun tube, including flamespread.

It should be noted that an excellent review on this overall topic is provided in "Modeling of Two-Phase Flow in Guns", by P.Gough, which is included in *Progress in Astronautics and Aeronautics*, Volume 66, published by the American Institute of Astronautics and Aeronautics (Ref.2-38).

Finally, Appendix III includes: (1) the description of a one-dimensional, two-phase flow interior ballistic problem supplied to workshop participants for treatment using the various operational codes, and (2) a compilation of results provided to this author as of the date of submission for publication.

REFERENCES

2-1	Hoog, K. Krauth, G.	*Vergleich zweier gasdynamischer Rechenmodelle der Innenballistik*, ISL-CO 219/76, 1976.
2-2	Hoog, K.	*Simulation innenballistischer Vorgänge in gasdynamischen Rechenmodellen*, in BMVg, FBWT 76-18, Ausgewählte Beiträge zur Ballistik, 1976.
2-3	Krauth, G.	*Anwendung eines Charaketeristiken-Verfahrens in Lagrangeschen Koordinaten in der Innenballistik*, in BMVg, FBWT 76-18, 1976.
2-4	–	*High, Rapidly Varying Temperatures*, PVI Etablissement Technique de Bourges 1614 MET.
2-5	–	*Measuring the Temperature at the Gun Tube Wall of a 120 mm Gun*, PVI Etablissement Technique de Bourges 1630 MET.
2-6	Prévot, M.	*Contribution to the Determination of Thermal Loss in Gun Tubes*, Report No.1, Note 2/CT/79.
2-7	Heinz, C. Hensel, D.	*Ein modifiziertes Lagrangesches Modell det Innenballistik*, Propellants and Explosives 2, pp.105-111, 1977.
2-8	Heiser, R.	*Hodographenverfahren für instationare eindimensionale Gasströmungen*, Forschungsbericht aus der Wehrtechnik BMVg-FBWT, 76-16, 1976.
2-9	Heiser, R. Klingenberg, G. Mach, H.	*Theoretical and Experimental Determination of Flow Properties Inside the Tube of a Gun*, Proceedings of the Third International Symposium on Ballistics, Karlsruhe, 23–25 March 1977.
2-10	Dürschner, M.G.	*Das verallgemeinerte Lagrange-Problem mit Verbrennung und dynamischer Relaxation*, Dissertation RWTH Aachen, 1976.
2-11	Dürschner, M.G.	*Anwendung der Gasdynamik auf die Innenballistik*, Diehl-Berichte aus Forschung und Entwicklung, 1977.
2-12	Heiser, R. Hensel, D.	*Calculation of the Axisymmetric Boundary Layer Flow Behind a Moving Projectile*, Proceedings of the Fourth International Symposium on Ballistics, Monterey, CA, USA, 17–19 October 1978, or ISL Report CO 221/78.
2-13	Hensel, D. Heiser, R.	*Achsensymmetrische Beschreibung der Gasstromung in einem Waffenrohr mit Hilfe der Navier-Stokes-Gleichungen*, ISL Report CO 222/79.
2-14	Gough, P.S.	*Modelling Heterogeneous Two-Phase Reacting Flow*, AIAA Journal, Volume 17, No.1, pp.17-25, January 1979.
2-15	Horst, A.W. Gough, P.S.	*Influence of Propellant Packaging on Performance of Navy Case Gun Ammunition*, Journal of Ballistics, Volume 1, No.3, pp.229-258, 1977.
2-16	Horst, A.W. Nelson, C.W. May, I.W.	*Flame Spreading in Granular Propellant Beds: A diagnostic Comparison of Theory to Experiment*, AIAA/SAE 13th Propulsion Conference, AIAA Paper No.77-856, July 1977.
2-17	Horst, A.W. Gough, P.S.	*Modeling of Ignition and Flamespread Phenomena in Bagged Artillery Charges*, Proceedings of the Fifth International Symposium on Ballistics, Toulouse, France, 16–18 April 1980.
2-18	Gough, P.S.	*Two Dimensional Convective Flamespreading in Packed Beds of Granular Propellant*, ARBRL-CR-00404, July 1979.
2-19	Fisher, E.B.	*Quality Control of Continuously Produced Gun Propellant*, Calspan Report No. SA-5913-X-1, Calspan Corporation, Buffalo, NY, August 1977.

2-20	Fisher, E.B.	*Investigation of Breechblow Phenomenology*, Calspan Report No. 1359-D-1, Calspan Corporation, Buffalo, NY, April 1979.
2-21	Kuo, K.K. et al.	*Transient Combustion in Mobile Gas-Permeable Propellants*, Acta Astronautica, Volume 3, pp.573-591, 1976.
2-22	Koo, J.H. Kuo, K.K.	*Transient Combustion in Granular Propellant Beds. Part I: Theoretical Modeling and Numerical Solution of Transient Combustion Processes in Mobile Granular Propellant Beds*, BRL Contract Report No.346, August 1977.
2-23	Davis, T.R. Kuo, K.K.	*Transient Combustion in Granular Propellant Beds. Part II: Experimental Study of Transient Combustion Processes in Mobile Granular Propellant Beds*, BRL Contract Report No.347, August 1977.
2-24	Krier, H.	*Predictions of Flamespreading and Pressure Wave Propagation in Propellant Beds*, BRL Contract Report No.275, November 1975.
2-25	Krier, H. Ragan, S. Van Tassell, W.F.	*Flamespreading and Combustion in Packed Beds of Propellant Grains*, AIAA Journal, Volume 14, No.3, pp.301-309, March 1976.
2-26	Gibeling, H.J. Buggeln, R.C. McDonald, H.	*The Development of a 2-D Implicit Interior Ballistics Code*, ARBRL-CR-00411, January 1980.
2-27	Buckingham, A.C.	*Dusty Gas Influences on Transport in Turbulent Erosive Propellant Flow*, AIAA Paper 80-0141, January 1980.
2-28	Kang, S.W. Levatin, J.A.	*Transient Compressible Boundary Layer Analysis*, 32nd Fluid Dynamics Meeting of the American Physical Society, Notre Dame, IN, November 1979.
2-29	Kooker, D.E.	*Transient Laminar Flame Propagation in Confined Premixed Gases: Numerical Predictions*, 17th Symposium (International) on Combustion, Leeds, England, August 1978.
2-30	Kooker, D.E.	*Numerical Predictions for Laminar Flame Propagation in Confined Ozone/Oxygen Mixtures: Influence of Initial Temperature and Pressure*, AIAA Paper 79-0292, January 1979.
2-31	Kooker, D.E.	*Numerical Predictions for Ignition of a Confined Reactive Gas*, BRL Technical Report ARBRL-TR-02037, January 1978.
2-32	Kooker, D.E. Nelson, C.W.	*Numerical Solution of Three Solid Propellant Combustion Models During a Gun Pressure Transient*, BRL Report No.1953, January 1977.
2-33	Schwegler, R.F.	*Evaluation of Two Blank Firing Attachments for the M2HB Caliber .50 Machine Gun*, R-TR-76-022, General Thomas J.Rodman Laboratory (SARRI-LS-P), Rock Island Arsenal, Rock Island, IL 61201, June 1976.
2-34	Goldstein, S.	*Qualitative Investigation of the Functioning of 7.62 mm Blank Ammunition*, Frankford Arsenal Technical Note TN-1141, June 1969.
2-35	Merkle, C.L. Turk, S.L. Summerfield, M.	*Extinguishment of Solid Propellants by Depressurization Effects of Propellant Parameters*, AIAA Paper No.69-176 (1969). Also AMS Report No.880, Princeton University, Princeton, NJ, 1969.
2-36	Kuo, K.K.	*Review of Dynamic Burning of Solid Propellants in Gun and Rocket Propulsion Systems*, 16th International Symposium on Combustion, pp.1177-1192, 15–20 August 1976.
2-37	Goldstein, S.	*Study of the Flow Through the Pressure Port in a Gas Operated Small Arms Automatic Weapon*, Frankford Arsenal Report FA-TR-76059, November 1966.
2-38	Gough, P.S.	*Modeling of Two-Phase Flow in Guns*, Progress in Astronautics and Aeronautics, Volume 66, *Interior Ballistics of Guns*, American Institute of Astronautics and Aeronautics, 1979.

Appendix I

INPUTS RECEIVED FOR FLUID DYNAMIC ASPECTS OF INTERNAL BALLISTICS FOR SECTION 2.1 INTERIOR BALLISTIC MODELS

Contributor	*Authors, Location, Title of Submission*
US Navy	1. Robbins, NOS/IH, "Improved Interior Ballistics"
US Air Force	2. Powers, AFAL, "Interior Ballistics Modeling"
US Army	3. Horst, Minor, BRL, "Interior Ballistic Modeling and Validation"
US Army	4. Kooker, BRL, "Ignition and Flame Modeling"
US Army	5. Goldstein, FC & SCWSL, "Interior Ballistic Modeling of Blank Ammunition"
England	6. Pagan, RMCS, "Study of Heat Transfer Between Gas and Solid, and Solid and Air; Development of 2-Phase Model of Propellant Burning Process"
France	7. SNPE/CRB, STPE, "Modeles de Balistique Interieure ID et IID"
France	8. ETBS-GIAT, DTAT, "Pertes de Chaleur et Mesures de Temperature a la Paroi d'un Tube d'Arme"
France	9. SNPE-CRB, DRET, "Modele de Balistique Interieure pour Canon a Ergol Liquide"
Germany	10. Heinz, Hensel, RWTH/ISL, "Calculation of the Internal Ballistic Flow"
Germany	11. Heiser, EMI-AFB, "One-Dimensional Interior Ballistic Flow Model"
Germany	12. Dürschner, et al., DIEHL, "One-Dimensional Two-Phase-Flow in Weapons including Ignition"
Germany	13. Carriere, et al., ISL, "Simulation of Interior Ballistic Phenomena in Gun Tubes Using One-Dimensional Gas Dynamic Computer Models"
Germany	14. Heiser, Hensel, EMI-AFB/ISL, "Two Dimensional Description of the Flow and Temperature Fields Inside of a Gun Tube"
Germany	15. Heinz, Mertens, RWTH, "Boundary Layer Calculation with Respect to Heat Transfer"

Appendix II

AGARD Workshop
THEORY AND MODELING OF INTERIOR BALLISTICS OF GUNS
ROYAL MILITARY COLLEGE OF SCIENCE, 22–24 APRIL 1980

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††	Workshop Co-Leader	‡‡	AGARD FDP Executive
*	Chairman, AGARD WG-05	☆	Host Chairman
**	Member, AGARD WG-05	☆☆	Host Secretary

Appendix III

GUN INTERIOR BALLISTICS MODELING EXERCISE

The following sample problem is designed for use with interior ballistic predictive schemes which can treat igniter gas injection and axial flamespreading phenomena. The gun geometry is a constant cross section cylinder as shown in Figure 1. The following are the input conditions:

Gun Tube:

* Diameter = 5.2 inches, constant
* Breech Face = 0.0 inches
* Projectile Base = 30.0 inches
* Muzzle = 200.0 inches
* Bore Resistance = 2000.0 psi, constant
* Heat loss to chamber and tube is negligible
* Obturation is perfect
* Gun is smoothbore

Projectile:

* Mass = 100 lbm

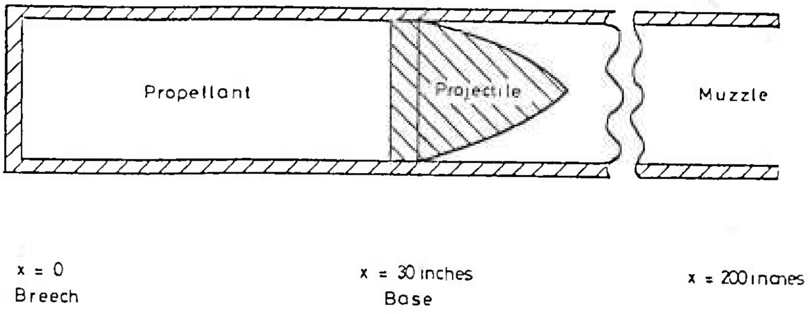

Fig. 1 Sample problem gun geometry

Propellant:

* Total Mass = 21 lbm
* Density = 0.057 lbm/in^3
* Grain Length = 1.0 inch
* Grain Diameter = 0.45 inch
* Perforation = 0.045 inch (7 each)
* Burn Rate = aP^n inches/sec
  a = 0.00035
  n = 0.9
* Adiabatic Flame Temp. = 4320 R
* Ignition Temperature = 800 R
* Thermal Conductivity = 0.0277 lbf/sec R
* Thermal Diffusivity = 0.0001345 in^2/sec
* Emmissivity = 0
* Chemical Energy = 15,000,000 (in-lbf)/lbm
* Molecular Weight = 21.3
* Specific Heats Ratio = 1.27
* Co-volume = 30
* Intergranular Wave Speed = 10,000 in/sec, reversible†

Igniter:

* Total Mass = 0.5 lbm
* Density = 0.065 lbm/in^3
* Chemical Energy = 6,303,000 (in-lbf)/lbm

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† A value of 17,400 in/sec was employed by DIEHL (Ge).

* Molecular Weight = 36.13
* Specific Heats Ratio = 1.25
* Adiabatic Flame Temp. = 3600 R
* Total mass of igniter gas is injected uniformly from 0 to 5 inches in 10 msec time span

Initial Conditions: * Ambient Air → T = 530 R
γ = 1.4
MW = 29
P = 14.7 psia
* Propellant Bed → T = 530 R

Model Comparison Parameters:

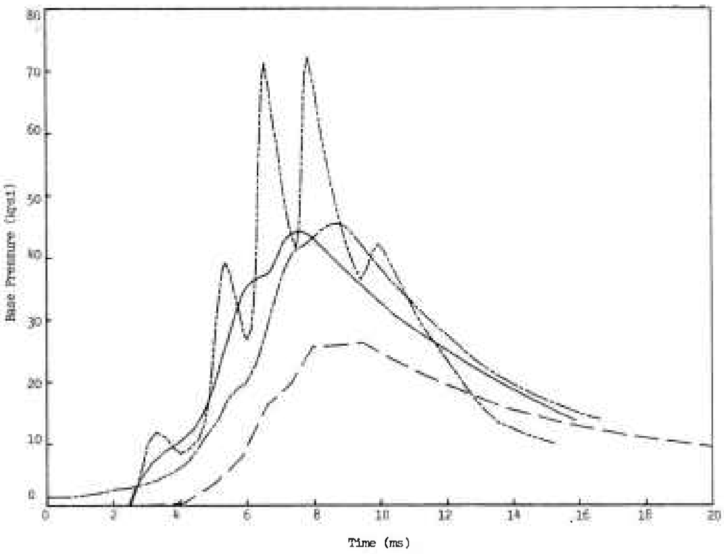
- Projectile base pressure vs time
- Projectile travel vs time
- Flame/ignition front vs time
- Gas pressure, density, temperature vs axial position at first projectile motion, at one inch of projectile motion, at 12 inches of projectile motion, and at muzzle exit.
- Solid-phase intergranular stress and temperature vs axial position at first projectile motion and at one inch of projectile motion.
- Propellant bed porosity vs axial position at one inch and 12 inches of projectile motion.

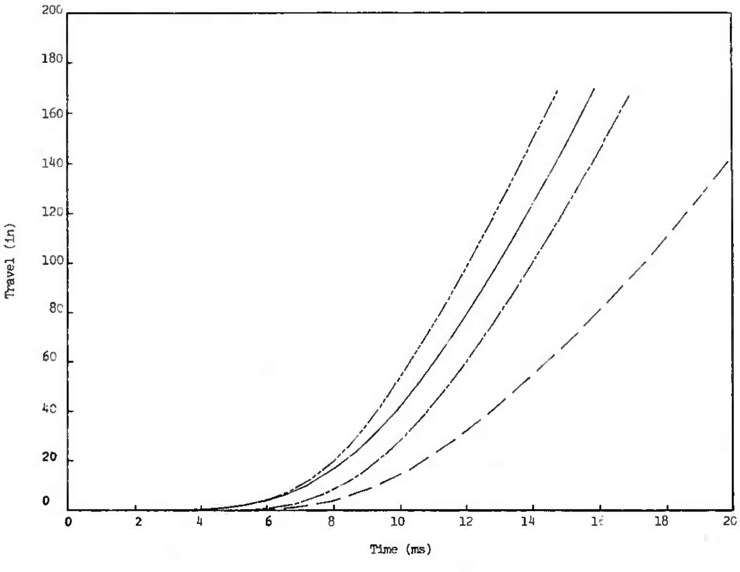
Results of Calculations:

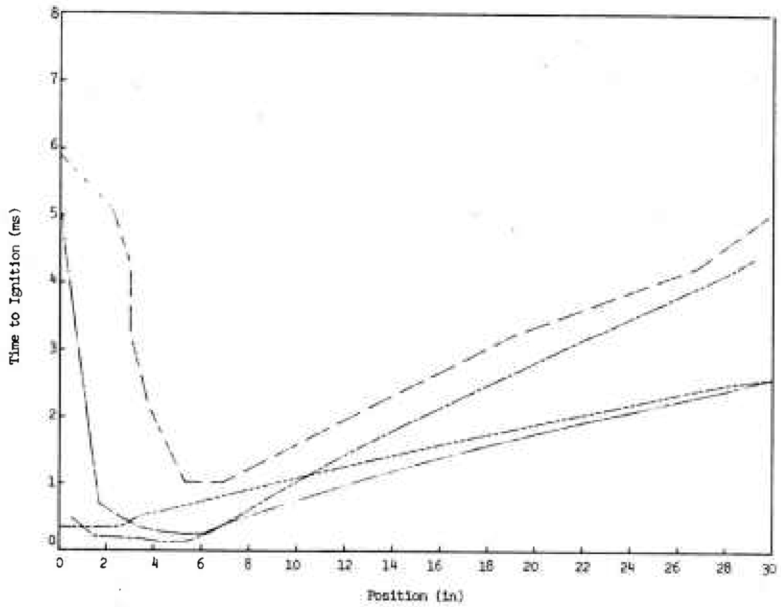
Legend:

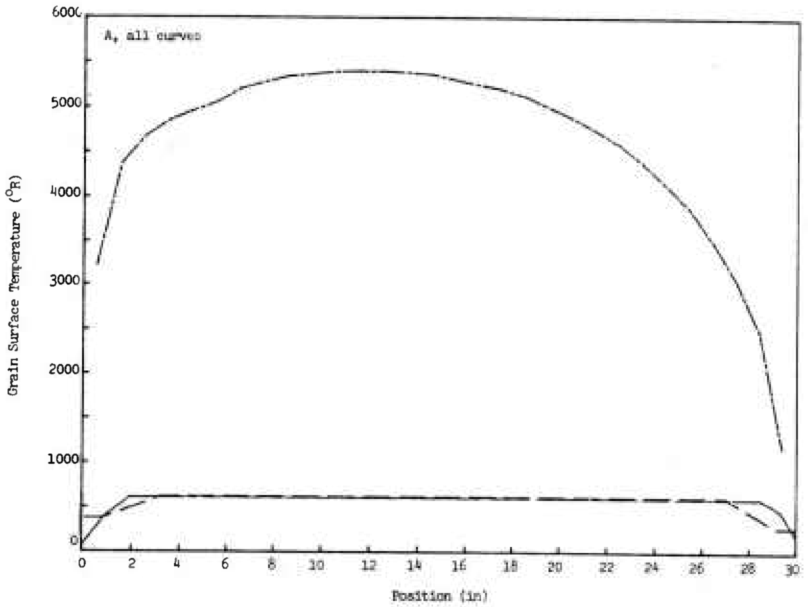
———— NOVA Code US
— — — SNPE Code (Fr)
— - — - - DIEHL Code (Ge)
— -- — -- CALSPAN Code (US)

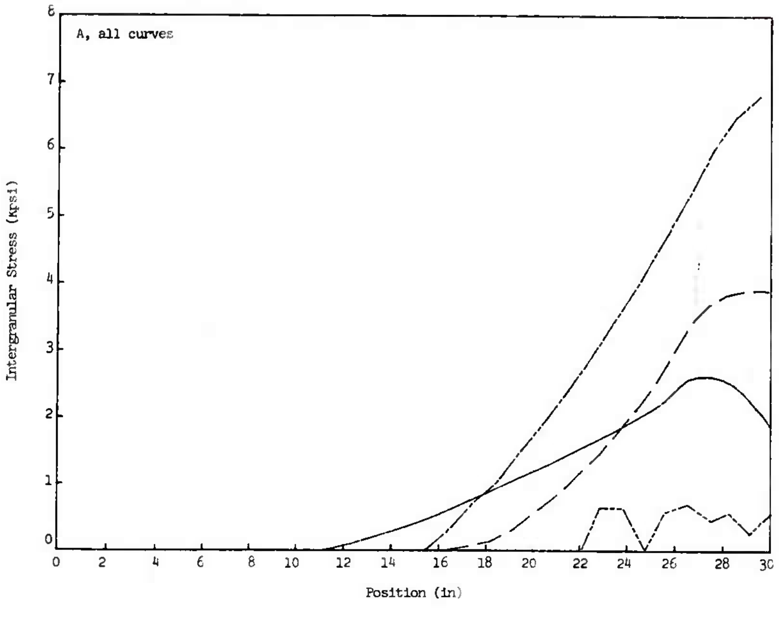
A – Data at first projectile motion
B – Data at 1″ of projectile travel
C – Data at 12″ of projectile travel
D – Data at muzzle exit






Time to Ignition (ms)
0
1
2
3
4
5
6
7
8
Position (in)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30


A, all curves
Grain Surface Temperature (°R)
0
1000
2000
3000
4000
5000
6000
Position (in)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30


A, all curves
Intergranular Stress (Kpsi)
0
1
2
3
4
5
6
7
8
Position (in)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
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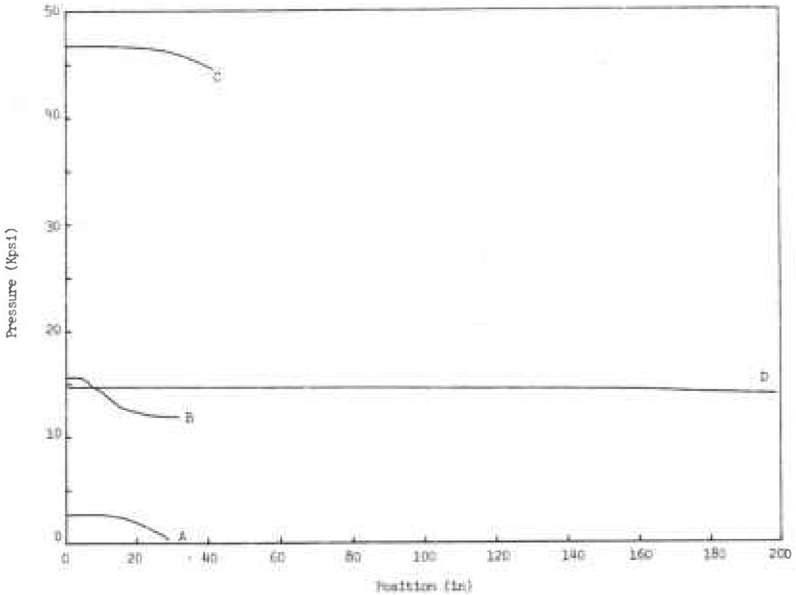
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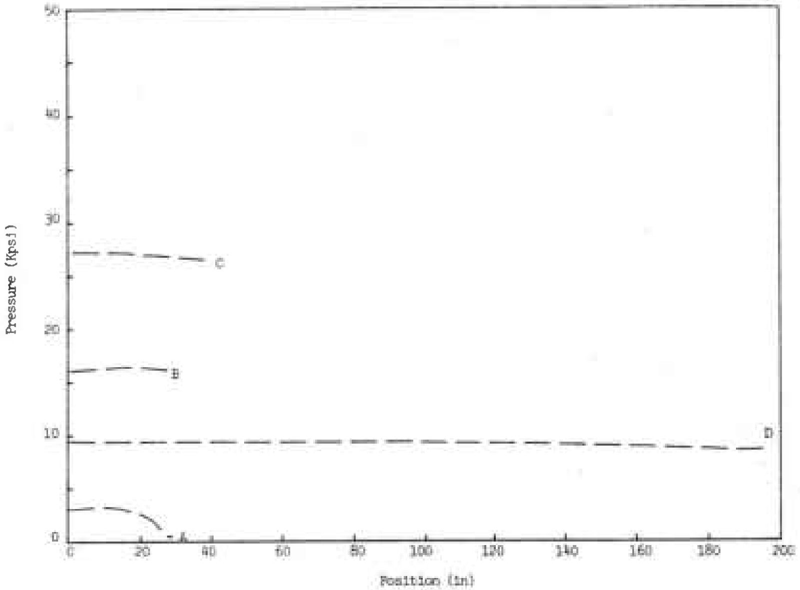
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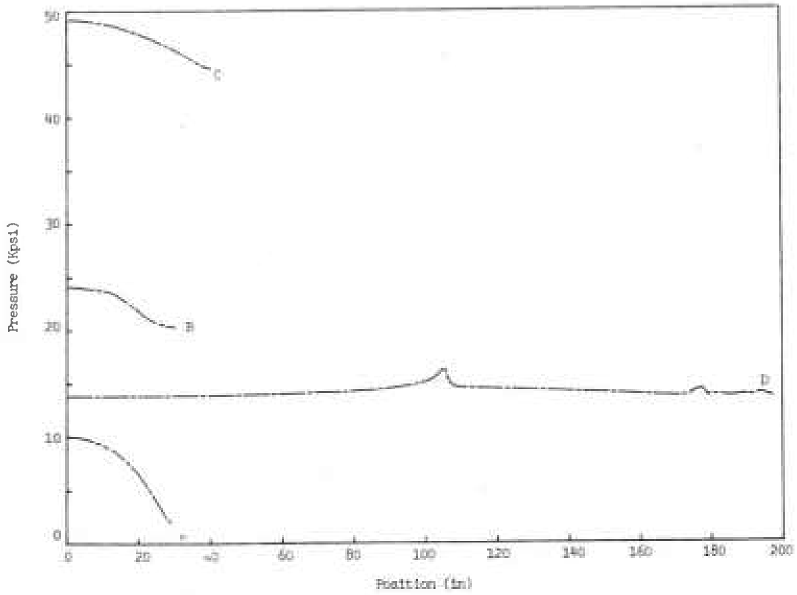
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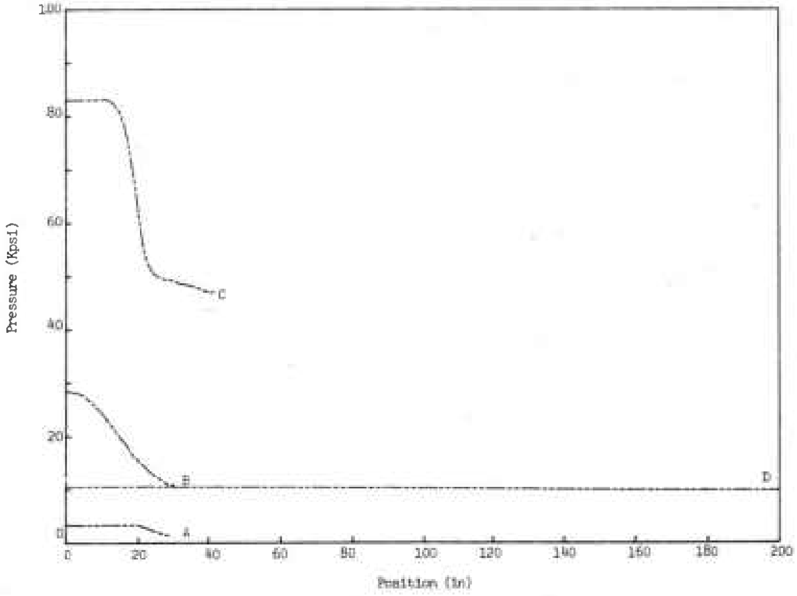
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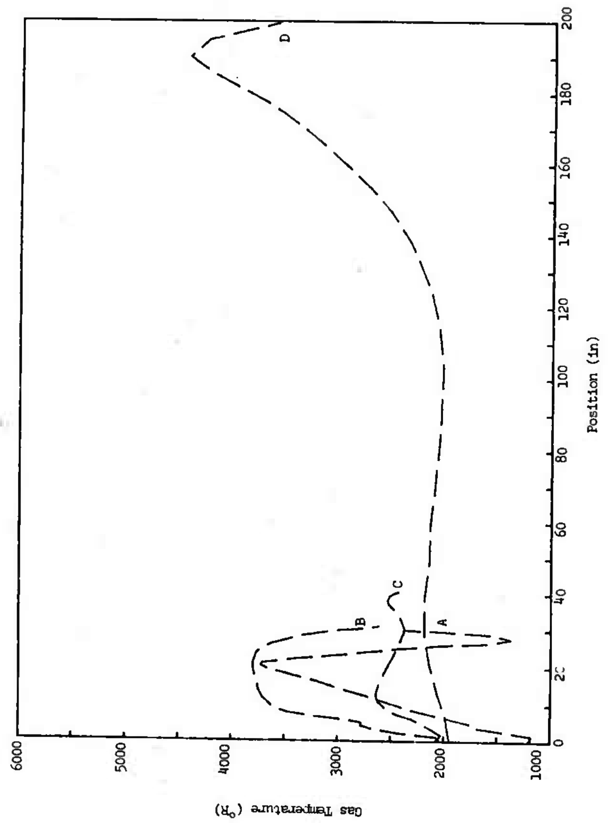
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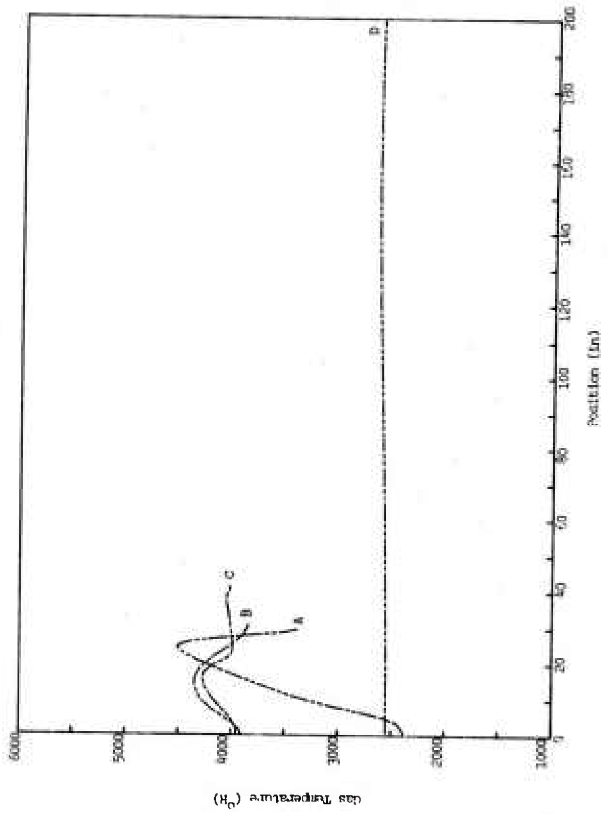
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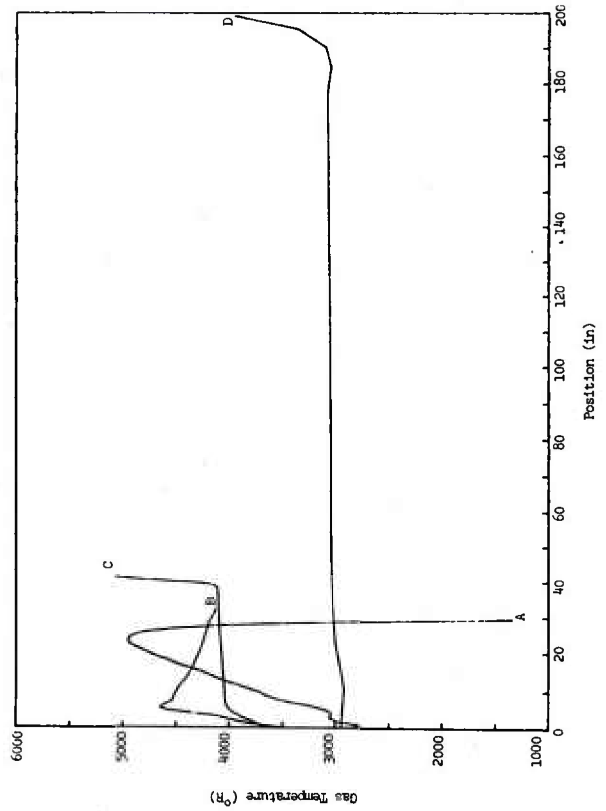
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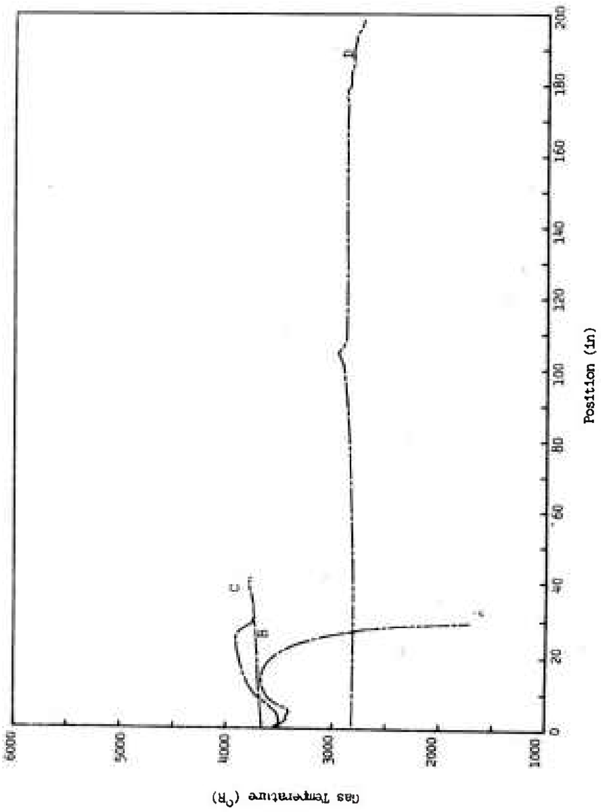
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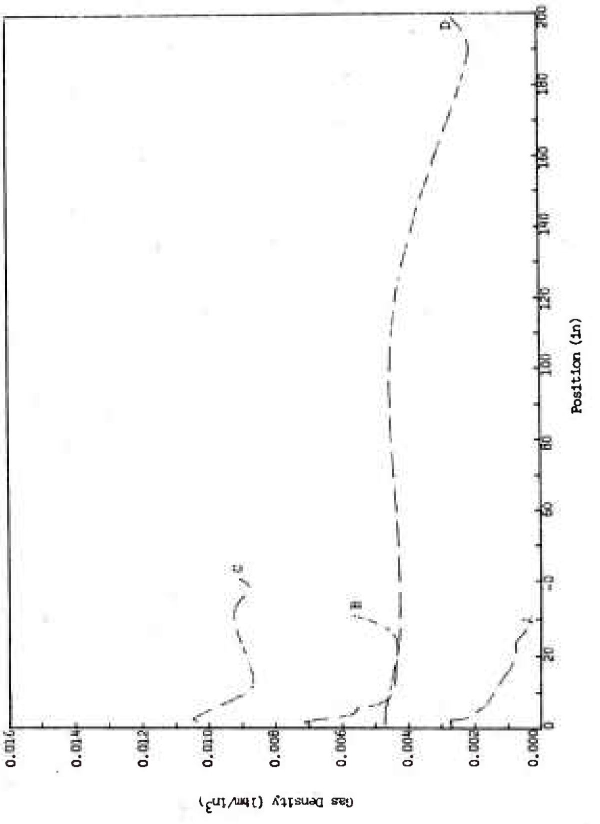
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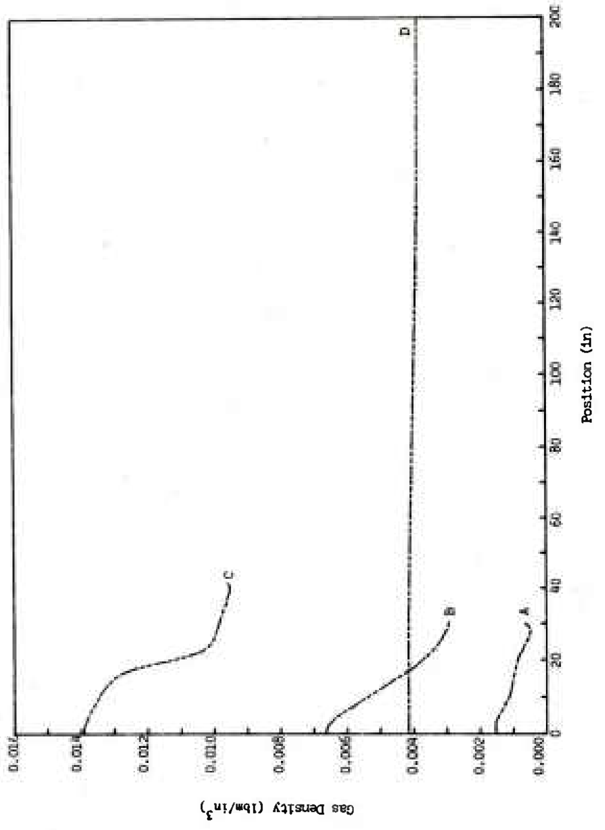
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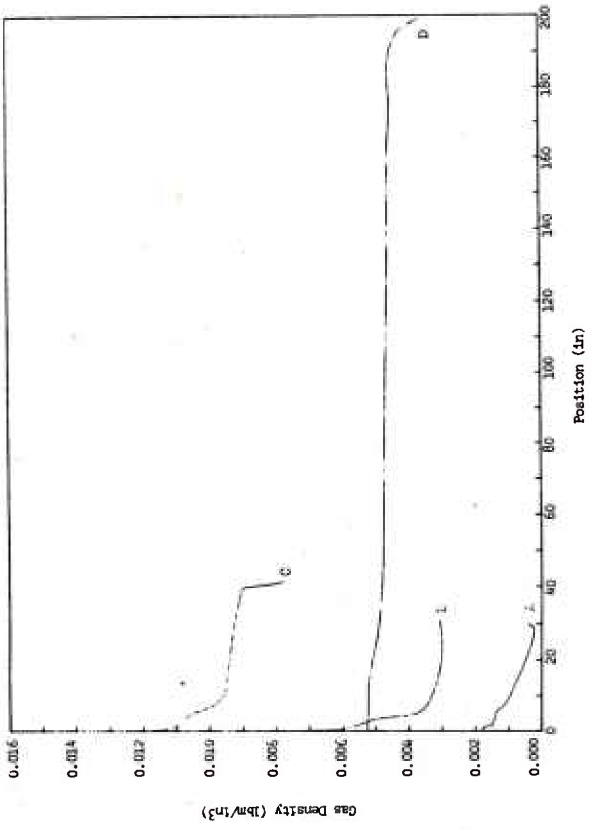
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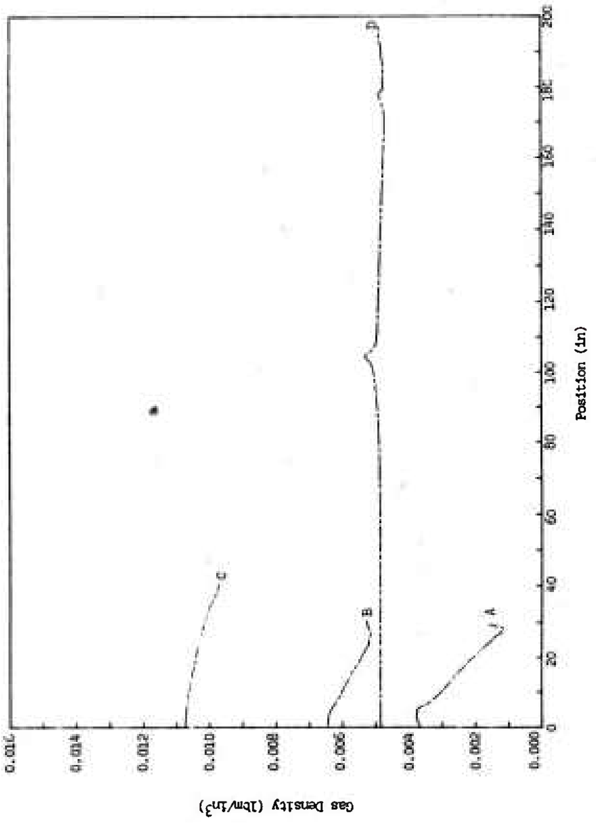
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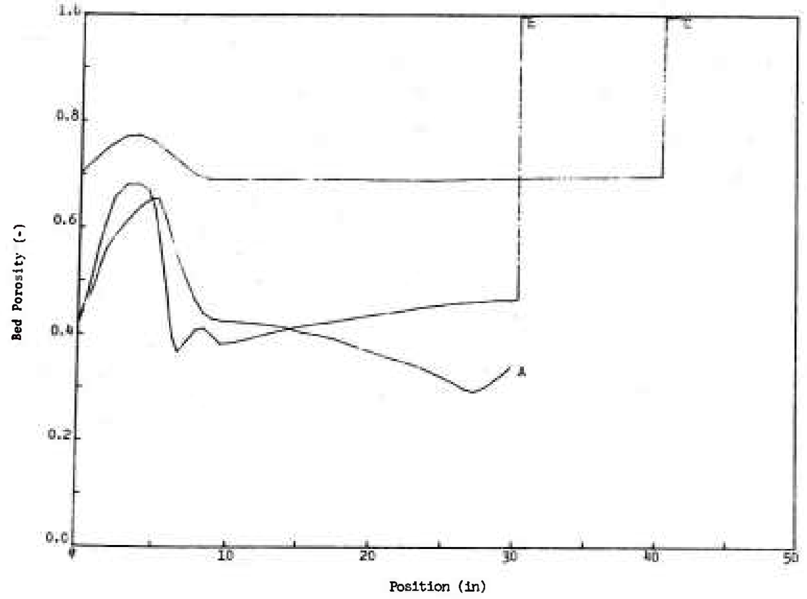
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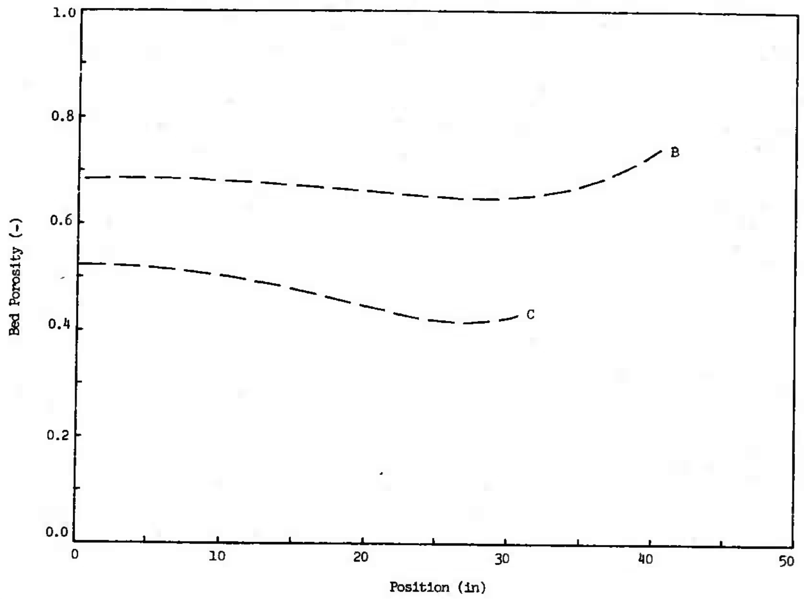
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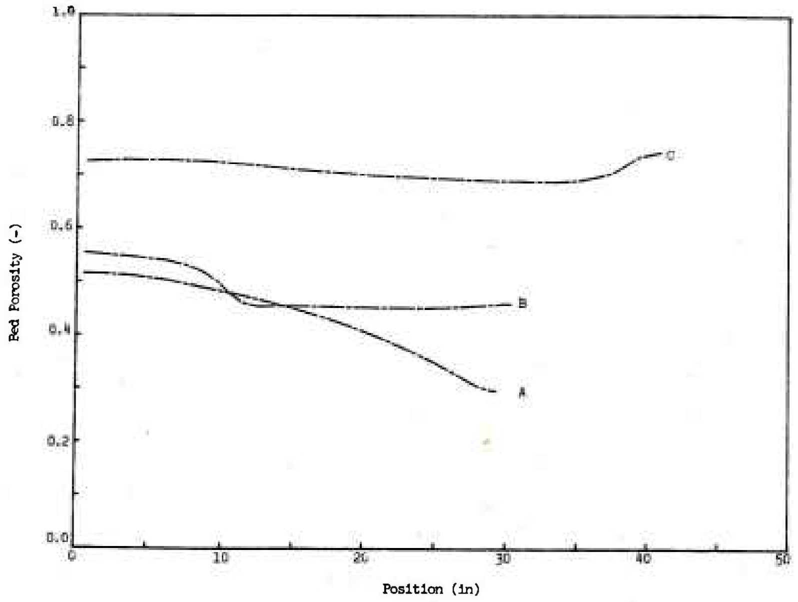
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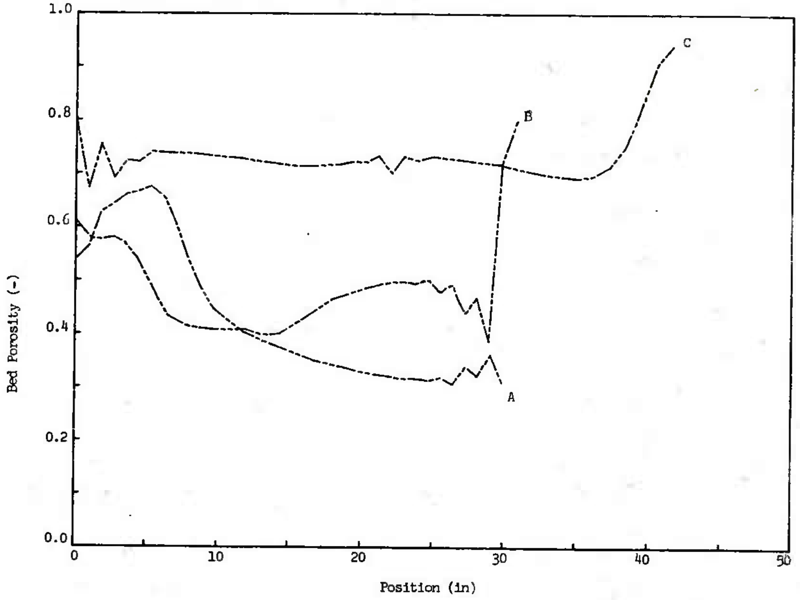
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2.2 SUPPORTING THEORY AND EXPERIMENTS

2.2.1 Ignition Processes in the Weapon

2.2.1.1 Flow Inside and Escaping from the Primer Tube or the Propellant Charge Igniter

Seven inputs are collected in this subsection, dealing with the phenomena occurring at ignition into the primer, or with igniter output characterization.

Most of them are of experimental kind; with few exceptions, they mainly refer investigations concerning suitable experimental techniques development and using, to carry out measurements of various parameters describing the phenomena occurring inside the igniter, or characterizing its output (to be used as input for two-phase flow models validation).

- The primer configuration and the priming mixture influence on the ignition "time" events, as the primer holes breaking, is being investigated at DTAT, Fr (Ref. 2-39). Tests were performed in air, in closed bomb, with or without the charge, and in the weapon, using a phototransistor detection system; see also Reference 2-40.
- A Laser Doppler Velocimetry (LDV) technique was developed at ISL, Fr, and jointly used by ISL and EMI, Ge (Ref. 2-41), to measure the gas velocity within reactive flows; this technique was successfully employed to carry out measurements of the space- and time-distribution of the gas velocity at the exit plane of charge igniters. Investigations are needed to take into account the velocity lag between the gas and the light scattering centres, i.e. the particles representing the condensed phase of the flow. References 2-42 to 2-47 report on the background of this activity.
- A quite complete igniter output characterization should be obtained by combining the LDV with other optical techniques and pressure measurements, as reported from EMI, Ge (Refs 2-42, 2-48). In fact, the igniter behaviour may be described in terms of:
  - the pressure distribution inside of and at the exit of the igniter;
  - the pressure distribution inside the blast field;
  - the flamespreading, and the spectrum of the flame;
  - the gas temperature and velocity at the exit plane of the igniter.

  Measurements of these quantities were just carried out at EMI, firing in open air a special igniter system developed by Dynamit Nobel AG, Ge, employing various priming substances, as black powder, nitrocellulose, boron-potassium nitrate. Next steps will involve firings into inert and propellant beds. The most important results are documented in References 2-49, 2-50.
- Another special technique has been especially developed at Hochschule der Bundeswehr of Hamburg, Ge, to investigate the igniter output characteristics, (Ref. 2-51); this technique makes use of a large high vacuum chamber where the igniter combustion products are dumped, to avoid secondary reactions, and remain in a "frozen" state. By means of a multi-channel, high time resulution (10 μs) mass spectrometer, installed in the vacuum chamber, the concentration of the gaseous reaction products and their velocity distribution are measured; similar information about the condensed reaction products are extracted employing special absorbers installed as well in the vacuum chamber. The experimental results are directly comparable with theoretical ones, computed by thermodynamic models to be validated. More detailed information on these techniques can be found in References 2-52 to 2-55.
- In the context of a German Working Group on ignition problems, an effort is ongoing at Dynamit Nobel AG, Ge, (Ref. 2-56), with the double purpose of establishing a mathematical model of the ignition phenomena, and new "ad hoc" measurement techniques development. Several experimental techniques have been developed, as isotope processes for the flame distribution within the case, mass spectrometry for the velocity distribution of various flame components, interrupted burning technique to quantify the ignition process. A hypothetical ignition model has been implemented, dealing in first line with a pure gas igniting flame, and the related erosive process of propellant grains; further improvements of measuring techniques are foreseen, in order to completely check the thermodynamic calculations and ignition model validity. As for the relevant literature, besides Reference 2-42, see also References 2-57 to 2-61.
- The small caliber primer characterization, in terms of energy output and its interaction with the propellant charge, will be performed at Small Caliber Lab, ARRADCOM, USA (Ref. 2-62). A suitable instrument has been designed, to allow the fluiddynamic experimental analysis of the combustion products: flame temperature measurements, output condensed phase and chemical composition analysis, for various priming mixtures. In order to avoid introducing effects of the percussion sensitivity, the primer ignition will be initiated via hot wire. At the same time, thermodynamic computations will be carried out by computer codes suitably developed.
- The black powder burning behaviour will be investigated during a planned work at BRL, ARRADCOM, USA (Ref. 2-63). A special vented bomb will be used, to quantify the powder geometry influence and confinement effects on burning rate.

2.2.1.2 *Propagation of Flow Flame Front and Pressure Waves Within the Charge (Bulk Powder used as Porous Material, Labyrinth Flows, Influence of the Flow on the Solid State Powder Particles), Powder Bed Rheology, Before and During Burning.*

Nine activities concerning this subsection are dealing with ongoing or planned experimental works.

- The correlation between the charge ignition delay time (or other "time" experimental parameters) and the primer characteristics (geometric, physical-chemical), is being investigated, for medium and small caliber weapons, at DTAT, Fr (Ref. 2-64). The pressure-time dependence is measured by firing in open air, in closed bomb (with or without propellant charge), or in the weapon; ignition time, suitably defined, is then deduced and correlated with other calculated parameters. By this method it has been established, for instance for ball powder, the great importance of the oxygen relative content in the igniting gases and of the flame temperature: the larger they are, the shorter is the ignition delay time. In the case of the 5.56 mm primer, it is found that ignition improvements are limited by the percussion sensitivity.

Several works are ongoing in Germany in this field, mainly consisting in special techniques set-up to investigate the various phenomena occurring inside gun tubes, due to the igniter gases and their interaction with powder beds.

- Neutron activation analysis and isotope x-ray analysis techniques, combined with igniter firings into a dummy polyethylene model of the charge, are useful in analysing the various gaseous and solid state components of the igniter output. First results obtained at Staatl. Forschunginstitut fur Geochemie, Bamberg, (Ref. 2-65) show a discontinuity in the distribution of some components, whose effects will be studied in the near future. References 2-66 and 2-67 document this activity.

- Pressure and flame propagation measurements and correlations with grains movements and mechanical pressure transfer from grain to grain were carried out at EMI/AFB, (Ref. 2-68). A special window-bomb with blow-out disc is used, 5.2 cm in length and 1.4 cm in diameter, fully instrumented with pressure and strain gauge transducers; a high speed camera (125.000 frames/s) is used to take pictures of the burning charge surface. Already conducted experiments using four experimental igniters of Dynamit Nobel AG (single or triple base powders) showed the correlation between the ignition time and initial pressure, as well as the strong contribution of the mechanical pressure transfer among grains to the pressure rise at the blow-out disc. Experiments with a larger chamber (20 mm cartridge) are planned, with measurements of heat transfer from gases to the grains. Details on this activity can be found in References 2-69, 2-70.

- The form, distribution and motion visualization of powder grains inside the chamber and the tube of a 20 mm gun is done at EMI/AFB, (Ref. 2-71), by high speed x-ray photography. The x-ray transparent barrels, made of fiber reinforced plastics, allow at present a maximum pressure of 350 MPa. References 2-72, 2-73 are related with the development of this technique.

- An experimental 90 mm gun with soft recovery equipment for the projectile, has been instrumented at EMI/AFB, (Ref. 2-74), for investigations on flame and pressure propagation (and first projectile motion). Small piezoresistive gauges and fiberglass light detectors are distributed inside the gun chamber; the signals are extracted through the blow-out disc, replacing the gun breech.

- The instrumentation of a 20 mm laboratory gun has been completed at ISL, Fr-Ge, (Ref. 2-75), which will allow investigations of pressure variations at different points of the charge, temperature profiles at the wall, and the flame front propagation. Optical methods and interrupted combustion technique will be used. By the same technique tests were conducted to investigate the behaviour of a powder charge simulated by ceramic elements.

Two ongoing efforts were reported from the Large Caliber Weapon Systems Lab., ARRADCOM, U.S., dealing with the flame propagation in the weapon and related problems.

- With the purpose of investigating the flow resistance through an inert solid bed of grains, a test chamber of 6" in diameter was assembled at a wind tunnel facility (Ref. 2-76). Filling the test section with inert grains of various geometries, supplying air from a 1" line, and measuring the pressure differences across the bed at different flow rates, the bed resistance is calculated. First results of this technique are presented in Reference 2-77. Improvements of the test facility are foreseen, to allow higher operating pressure and mass flow.

- A full scale 155 mm Howitzer simulation chamber is also under development (Ref. 2-78), allowing measurements of pressure, temperature and flame front propagation. Preliminary tests, already conducted with a slightly reduced chamber, showed the influence of the propellant packaging level and of the igniter configuration on the pressure spikes generation and traveling within the chamber.

- Optimization studies of the igniter/charge configuration for large calibers (5" and 8") are ongoing at NAVSWC, Dahlgren, U.S. (Ref. 2-79). Improvements of the propulsion cycle reproducibility, together with a reduction of the dynamic load on the projectile by moving propellant grains, have been obtained with a proper igniter design. In fact, several experimental "Rapid Ignition Propagation" (RIP) igniters were developed, using "Mild Detonation Fuzes" (MDF), to increase the axial ignition rate; so, the axial pressure waves and the related projectile loadings, occurring with the black powder, were substantially reduced. Many experimental techniques were set up and used during the study; among others: high speed photography of igniter firings in open air; igniter pressure measurements when fired into inert beds; flamespreading and pressure waves in the propellant bed recording, by firing in thin wall transparent gun tubes; propellant bed motion visualization, by means of x-ray photography; projectile response determination, by use of fast accelerometers and large face pressure gauges.

2.2.2 **Inflammation and Burning**

2.2.2.1 Investigation of Both Chemical and Physical Phenomena Occurring in the Inflammation and Burning of Propellant Particles in a Hot Gaseous Flow (Heat Transfer from Gas to the Propellant, Temperature Profile in the Propellant, Criteria for the Inflammation of the Individual Particle)

Thirteen inputs may be collected mainly concerning the above outlined subjects; here also the experimental works prevailing on the theoretical ones is to be emphasized.

- Investigations about the inflammation law of the propellant charge and its influence on the overpressure phenomena observed during the ignition are ongoing at SNPE, Fr, Reference 2-80. Current models of the powder inflammation are based on the critical surface temperature concept. Experiments on the powder inflammation and measurements of the surface temperature, when the ignition is done by radiant steady heat flux, have been carried out. A new measurement technique for the radial distribution of the modifier in surface coated propellants via microhardness measurements has also been successfully developed, as showed in Reference 2-81.

- The profile of coating concentration across the propellant is also being investigated at Erprobungsstelle Meppel, Reference 2-82. Interrupted burning techniques together with chemical analysis, chromatographic techniques, as well as investigation of heat of explosion are used.

- Correlations between the enthalpy of condensable products escaping from the igniter and the ignition delay time have been established at ICT Pfintzal, Ge, Reference 2-83. Several ignition mixtures were experienced, containing B, Mg, Al, Zr as fuels and Barium-nitrate as oxidizer. By firing charges of surface coated propellant in the ballistic bomb, the effectiveness of the various ignition mixtures was compared; the Zirconium/Barium-nitrate showed a very effective ignition behaviour. Theoretical models were developed, to determine “a priori” the ignition efficiency of new formulations. Future work will investigate the behaviour of other oxidizers, like KNO_3 and $KClO_4$. The background of this research is described in Reference 2-84.

- The inflammability of a solid propellant depends from the pressure end temperature values; an investigation is planned at ISL, Fr-Ge, Reference 2-85 to find this interrelation. A special high pressure closed bomb will be used, allowing the simultaneous firing of two charges of the same type; the gases from the first charge will ignite the second one after a certain delay time; by measuring the pressure variations of the second charge, it is possible to evaluate the propellant inflammability. The gas temperature measurement will be done by optical means. Obtained results should allow calculations of heat conductivity and specific heat; moreover, using a calibrated substance, it will be possible to establish the temperature distribution law. Two ongoing efforts in this field were reported from U.S. Navy Agencies, respectively related with mechanical/ballistic properties of burning propellants and with ignition energetics.

- The first input (Ref. 2-86) describes an experimental work, just completed at NAVSWC/DL, investigating the mechanical contribution to the regression rate exhibited by a burning propellant in a highly transient pressure environment; a microwave-Doppler-phase-shift technique was used, as below outlined. Two coherent microwave signals passing through the base ends of two identical propellant strands, are reflected from the opposite sides of each strand. Although exposed to the same pressure environment, only one strand is burning; then, by continuously comparing the phase difference of the two reflected waves, it is obtained the rate of change of the phase difference, which should be proportional to the instantaneous burning rate of the propellant. Burning rate tests on M6 propellant in the pressure range of 3 to 70 MPa, steady state, were successfully performed; the technique was then extended to high pressurization rates (500 to 10 000 MPa/s), showing some problem affecting the results accuracy. Major difficulties are due to non-planar burning of the propellant, and to the not exactly synchronized mechanical response of the twin strand. Much information on this technique is given in References 2-87 to 2-91.

- The second input (Ref. 2-92) describes a program ongoing at NAVORDSTA, Indian Head, aimed to experimentally establishing the amount of energy deposited prior to ignition, the rate of energy deposition, as well as the influence of composition of both the primer and the propellant. The gas enthalpy measurement will be done by a suitable “Ignition Energetics Characterization Device” (IECD), especially designed, consisting of a vented constant volume bomb coupled with a mixing chamber lined with a material having a well known latent heat of fusion. Ignition requirements of gun propellants will be assessed, varying the ignition mixture (black powder, $BKNO_3$, nitrocellulose); flamespreading measurements in porous beds will also be done to be compared with codes predictions. Two papers reporting the ongoing activity in the standard and advanced propellants area at Air Force Armament Lab., Eglin Base, US, were announced.

- The first one (Ref. 2-93) is a gun propellant evaluation program; besides the immediate goal of standard and experimental propellants characterization, the long term objective is connected with the formulation and processing of advanced propellants. Correlations of strand and closed bomb burning rates measurements have already been completed for standard propellants, in the context of the JANNAF Burning Rate Workshop; similar correlations will be carried out for experimental gun propellants, in the region of 15 to 350 Mpa. Among others, image analyzer automated particle sizing techniques will be developed.

- The other one, Reference 2-94, is devoted to a basic research work in the field of new propellants formulations, having low flame temperature (2300°K), low gas molecular weight (18), and high mass impetus (1000 000 m kg/kg). This would be achieved with suitable Nitramine compounds having high binder-to-solid ratio. Two measurement techniques in the field of propellant combustion are being implemented at Large Caliber Weapon Systems Lab./ ARRADCOM, U.S.; see References 2-95, 2-96.

- Temperature and composition maps in the propellant flames may be obtained by means of Raman spectra. An equipment consisting of a beam generator (Nd/YAG laser, 700 mj x 10 ns, and dye laser) and a high resolution monochromator coupled with an optical multichannel analyzer, will be set up; the calibration of the system will be performed by atmospheric flames and heated pure gases (N_2, CO etc.). Accuracy and applicability limits of this technique will also be investigated.

- Closed bomb firings are still the first approach to the propellant performance assessment; the program mentioned in Reference 2-96 is aimed to make more meaningful and accurate such measurement technique. First of all, to achieve this objective, improvements are needed in the measuring equipment and data reduction system; therefore, a 700 MPa, 200 cm^3, single opening closed bomb has been developed, equipped with new pressure transducers and a faster sampling data acquisition system. On the other hand, a better heat loss accounting and state equation improvements are needed for accurate burning rate calculations; also these aspects are being studied. Three inputs, coming from BRL/ARRADCOM, U.S., are mainly dealing with transient modeling and consolidated charges investigations.

- The transient regression rate during chamber pressurization is being theoretically investigated (Refs. 2-97 to 2-100). First results of model computations show that the use of some temperature-dependent thermal characteristics decreases the transient response and slows down the temperature rise of the propellant surface in heating up to the ignition. The use of Laser Velocimetry technique will be investigated to measure the regression rate in order to check the model.

- The flamespread phenomenology in consolidated charges is being experimentally investigated, using samples of various compaction levels (Ref. 2-101). Gas flow permeability measurements showed extremely high interphase drag values. The mechanical solicitation of grains during the compaction process seem to be quite inconsequential with respect to the burning behaviour, except at low pressure, where the recorded reduced mass generation rate may be attributed to a delayed flame penetration through the charge. Likewise, by using a thick walled Lexan chamber, flame propagation velocities of the same order (350 to 400 m/s) were measured both for consolidated and unconsolidated samples, with some erratic behaviour for the higher compaction level charges. The present progresses point out several critical areas in the field of consolidated charges; first of all, the reproducibility of the flame penetration into the charge is to be improved. The role of the propellant fracture mechanics will be investigated.

- Another study is planned (Ref. 2-102) concerning, among others, a propellants characterization to the double purpose of consolidated charges study and traveling charges improvement. Conventional and super high burning rate propellants will be investigated too, using typical closed bombs and special blow-out fixtures. Reproducibility of combustion behaviour and transient response will be the main subjects of the analysis. The main facility to be employed and the related data reduction system are described in Reference 2-103.

- The development of a single consolidated charge loading for a 30 mm gun has been commenced at SNPE, FR, Reference 2-104. Already conducted experimentation showed the existence of three distinct phases: a first phase of inflammation, a second one of charge fragmentation, and a third phase of flame penetration into the powder. The main aim of the work – 10% of performance improvement, in terms of initial velocity of the projectile – has been easily reached, but with a larger dispersion. The reasons of such a performance dispersion has been analyzed in functions of the three above mentioned phases.

2.2.2.2 Influence of the Flow on the Powder Burning (Influence of Relative Velocity, Temperature and High Pressures; Erosive Burning)

Three inputs may be gathered under the above heading, specifically concerning the erosive burning of propellant particles and the dynamics of solid propellant combustion; moreover, some of the activities mentioned in the previous sub-section has some aspect related with the present subject (see for instance References 2-86 to 2-91 and 2-97 to 2-100).

- Investigations about the stagnation point flow of spherical propellant particles are ongoing at Diehl, GE (Ref. 2-105). Numerical computations of burning rate of a solid propellant for either heterogeneous endothermic (pyrolysis), or homogeneous exothermic two-step reactions have been carried out for various flow temperature and velocity values. Negative or positive burning rate contribution have been found, when the effects of the flow field around the propellant grain are considered. The analysis will be continued, varying the pressure and/or the activation energy.

The burning behaviour of propellants under variable pressure conditions is being studied, either theoretically, at Politecnico di Milano, IT, or by experiments, at NAVORDSTA, Indian Head, U.S.

- A thermal theory of heterogeneous combustion was formulated and non-linear burning stability analyses were performed, showing a propellant unsteady behaviour. In fact, an upper dynamic instability, due to fast pressurization, was theoretically predicted and numerically verified for propellants having large surface heat release. The background of this activity is contained in References 2-106 to 2-112. Improvements of flame models are planned, and comparison with experimental results will be performed.

- The burning rate dependence upon the pressure time derivative is being experimentally investigated by means of a special system, consisting of a ballistic compressor connected with a vented combustion chamber by a fast acting shut-off valve; a suitable instrumentation for ignition detection and pressure measurements, as well as the data reduction system, are included in the facility. An overall mathematical model is being implemented, allowing the burning rate computation, starting from the measured pressure histories in both the compressor and the combustion chamber. Reference 2-113 relates the already done activity, as well as a planned investigation on the burning behaviour under fast depressurization conditions, by a proper sizing of venting hole and propellant grains geometry.

REFERENCES

2-39	–	GIAT, DTAT, Private Communication, November 1980
2-40	Benhaim, P. et al.	SNPE, Fr, *Rupture des Fonds de Douilles Combustibles a l'Allumage en Arme de Gros Calibre,* 5ème Symposium Internationale de Balistique, Avril 1980, Toulouse, Fr.
2-41	Mach, H. Smeets, G. Klingenberg, G.	ISL-EMI/AFB, Fr-Ge, Private Communication, November 1980.
2-42	Klingenberg, G. Wieland, O.	EMI/AFB, Ge, *Untersuchungen der Eigenschaften von vier Experimentier-TLANZ beim Abfeuern in den freien Raum,* 1979, EMI/AFB Report.
2-43	Smeets, G. George, A.	*Instantaneous Laser Doppler Velocimeter Using a Fast Wavelength Tracking Michelson Interferometer,* Rev. Sci. Instrum., Volume 49, No. 11, 1589-1596, November 1978.
2-44	Mach, H. et al.	ISL, Fr, *Beitrag zur Optischen Untersuchung von Treibladungsanzundern,* ISL-Notiz 1979.
2.45	Mach, H. et al.	ISL, Fr, *Geschwindigkeitsmessungen in Instationaren Stromungen mittels eines Laser-Interferenz-Velocimeters,* ISL-Report CO 204/78, 1978.
2-46	Klingenberg, G. Scroder, G.A.	*Investigation of Combustion Phenomena Associated with the Flow of Hot Propellant Gases; Gas Velocity Measurements by Laser-Induced Gas Breakdown,* Journal Combustion and Flame, 27, 177-187, 1976.
2-47	Klingenberg, G. et al.	*Gas Velocity Measurements within Reactive Propellant Gas Flows,* AIAA Journal (to be published).
2-48	Klingenberg, G.	EMI/AFB, Ge, Private Communication, November 1980.
2-49	Klingenberg, G.	*Bestimmung der fur den Abbrand von Treibladungen massgeblichen Eigenschaften von Experimentier-TLANZ,* Proceedings ICT, 10. Internationale Jahrestagung: Combustion and Detonation Processes, June 1979, Karlsruhe, GE.
2-50	Klingenberg, G.	*Energy Output of Different Pyrotechnic Igniter Systems,* Proceedings 7th International Pyrotechnics Seminar, July 1980, Vail, Colorado, USA.
2-51	Trinks, H. Schilf, N.	Hochschule der Bundeswehr, Hamburg, Ge, Private Communication, November 1980.
2-52	Trinks, H. Schilf, N.	*Short Time Diagnostic of Combustion and Detonation Processes by Dynamic Multi-channel Mass-Spectrometry and Condensate Analysis,* ICT, International Conference Combustion and Detonation Processes, 1979.
2-53	Schilf, N.	*Massenspektrometrische Analyse an Detonationsschwaden im Vakuum,* Dissertation HSBw-HH-TH Aachen, 1979.
2-54	Trinks, H. Schilf, N.	*Gasdynamic Investigation of Lead-Azid-Trizinat Detonation Processes in Vacuum by Multichannel-Mass-Spectrometry,* 7-th Int. Colloq. Gasdyn. of Explosions and Reactive Systems, Gottingen, August 1979, accepted December 1979 in Acta Astronautics.
2-55	Schilf, N. Trinks, H.	*Investigations about Ignition Processes by Short-Time Photography, Multichannel Mass Spectrometry and Condensate Analysis,* 5-th Int. Symp. Ballistics, Toulouse, April 1980.

2-56	Brede, U. Penner, H. Zeiher, E.	Dynamit Nobel AG, GE, Private Communication, November 1980.
2-57	Brede, U.	*Gegenuberstellung des Anzundverhaltens von Schwarzpulver und Borkaliumnitrat nach der Methode der unterbrochenen Anbrenntechnik,* Internationale Jahrestagung, ICT, Karlsruhe, 1979.
2-58	Bernstein, S.	*Methode zur Analyse der TLP-Entzundung unter Verwendung unterbrochener Brenntechniken,* Picatinny Arsenal, Dover, NY USA.
2-59	Zimmermann, G.	*Untersuchung zur Einwirkung der Anzunschwaden von Experimentier-TLANZ auf geschuttetes TLP,* Jahrestagung ICT, 1979.
2-60	Adomeit, G. Hocks, W.	*Zundung und erosiver Abbrand,* Symposium Leistungssteigerung von leichten Rohrwaffen, ICT, Karlsruhe, 1978.
2-61	Brede, U.	*Ein elektrischer Experimentier-TLANZ zum Studium von Anzundvorgangen, Deutsch-Franzosischer Datenaustausch,* Bouchet, Paris, 1977.
2-62	Stiefel, L. Doris T.A. Jr	*Fire Control and Small Caliber Weapon Systems Lab.,* ARRADCOM, USA, Private Communication, November 1980.
2-63	Sassé, R.A.	BRL ARRADCOM, USA, Private Communication, November 1980.
2-64	–	GIAT, DTAT, Private Communication, November 1980.
2-65	Meier, H. et al.	Staatl. Forschunginstitut fur Geochemie, Bamberg, Ge, Private Communication, November 1980.
2-66	Meier, H. et al.	*Isotopentechnische Untersuchungen von Anzundvorgangen,* Symposium Innenballistische von Rohrwaffen, Karlsruhe 1978.
2-67	Schroder, G.A. Hornemann, U.	*Visualization of Combustion and Flow Phenomena in Interior Ballistics,* 2nd Int. Symposium on Ballistics, Daytona Beach, March 1976.
2-68	Schmolinske, E. Zimmermann, G.	EMI/AFB, GE, Private Communication, November 1980.
2-69	Schmolinske, E. Zimmermann, G.	*Investigations in the Effect of the Gases of Experimental Igniters in Porous Propellant Charges,* Proceedings Jahrestagung des ICT Pfinztal-Berghausen uber Combustion and Detonation Processes, June 1979, 23-40.
2-70	Schmolinske, E. Zimmermann, G.	*Untersuchungen zur Wechselwirkung zwischen Treibladungsanzunder und Treibladung in einer speziellen Versuchseinrichtung,* Vortrag beim V Symposium *Innenballistische Leistungssteigerung von Rohrwaffen* bein BICT Swisttal-Heinerheim, December 1979.
2-71	Hornemann, U.	EMI/AFB, GE, Private Communication, November 1980.
2-72	Hornemann, U.	*Investigation of Propellant Combustion in X-Ray Transparent Gun Tubes,* 4-th Int. Symposium on Ballistics, Monterey, USA, October 1978.
2-73	Zimmermann, K. Remy, R.	*Untersuchungen zur Anzundvorgang,* ISL-Notiz N/607/76.
2-74	Grumann, H. Gutlin, E. Zimmermann, G.	EMI/AFB, GE, Private Communication, November 1980.
2-75	Zimmermann, G.	ISL, FR/GE, Private Communication, November 1980.
2-76	Schlosberg, L.P.	*Large Caliber Weapon Systems Lab.*/ARRADCOM, US, Private Communication, November 1980.
2-77	Kuo, K.K. Hydegger, C.C.	*Flow Resistance Measurements and Correlation in a Packed Bed of WC870 Ball Propellants,* Mech. Eng. Dept. of Pennsilvania State University, Contract DAAG 29-74-G-0116, July 1977.

2-78 Schlosberg, L.P. *Large Caliber Weapon Systems Lab.*/ARRADCOM, US, Private Communication, November 1980.

2-79 East J, Foster, J. NAVSWC, Dahlgren, US, Private Communication, November 1980.

2-80 – SNPE, STPE, FR, Private Communication, November 1980

2-81 Couturier, R. et al. *Microdureté appliquée aux poudres à la nitrocellulose,* Int. Jahrestagung, Karlsruhe, June 1977.

2-82 Jahnk, H. Erprobungsstele Meppel, GE, Private Communication, November 1980.

2-83 Hund, M. Volk, F. ICT Pfinztal, GE, Private Communication, November 1980.

2-84 Hund, M. Volk, F. Lenji, M.L. *Influence of the Reaction Products of Ignition Powders on the Ignition Behaviour of a Surface Coated Gun Propellant,* Proc. 4-th Int. Symposium on Ballistics, Monterey 1978.

2-85 Grune, D. ISL, FR/GE, Private Communication, November 1980.

2-86 Russel, L.H. NAVSWC/DL, US, Private Communication, November 1980.

2-87 Alkides, A. et al. *Measurement of Steady State and Transient Solid Propellant Burning Rates with Microwaves,* Final Report, Grant N. AFOSR-70-1934, December 1973, Georgia Institute of Technology, Atlanta, US.

2-88 Strand, L.D. Shultz, A.L. Reedy, G.K. *Determination of Solid Propellant Transient Regression Rates Using a Microwave Doppler Shift Technique,* Technical Report 32-1569, 1972, IPL, Pasadena, US.

2-89 Strand, L.D. Shultz, A.L. Reedy, G.K. *Microwave Doppler Shift Technique for Determining Solid Propellant Transient Regression Rates,* J. Spacecraft & Rockets, Volume 11, No. 2, Feb. 1974, pp. 75-83.

2-90 Strand, L.D. McNamara, R.P. *Feasibility of a Variable Frequency Driver-Microwave Transient Regression Rate Measurement System,* Progress in Aeronautics and Astronautics, Volume 63, Experimental Diagnostics in Combustion of Solids, AIAA, NY, 1979, pp. 155-172.

2-91 Russel, H.H. *Burning Velocity of a Solid Propellant via a Microwave Technique at Elevated Pressure and Pressurization Rates,* Ph.D. Dissertation, University of Pittsburg, US, 1979.

2-92 Irish, C.G. Jr NAVORDSTA, Indian Head, US, Private Communication, November 1980.

2-93 Moy, B.K. Eglin Air Force Base, US, Private Communication, November 1980.

2-94 Whidden, J.H. Eglin Air Force Base, US, Private Communication, November 1980.

2-95 Harris, L.E. Large Caliber Weapon Systems Lab./ARRADCOM, US, Private Communication, November 1980.

2-96 Lenchitz, C. Large Caliber Weapon Systems Lab./ARRADCOM, US, Private Communication, November 1980.

2-97 Nelson, C.W. BRL/ARRADCOM, US, Private Communication, November 1980

2-98 Kooker, D.E. Nelson, C.W. *Numerical Solution of Three Solid Propellant Combustion Models During a Gun Pressure Transient,* BRL Report No. 1953, January 1977. See also ASME Paper 77-H7-17.

2-99 Nelson, C.W. Robbins, F.W. Gough, P.S. *Predicted Effects of Transient Burning on Gun Flamespreading,* Memorandum Report ARBRL-MR-02830, April 1978.

2-100 Nelson, C.W. *Response of Three Types of Transient Combustion Models to Gun Pressurization,* Combustion and Flames, 32, 317-319, 1978.

2-101	May, L.W.	BRL/ARRADCOM, US, Private Communication, November 1980.
2-102	Juhasz, A.A.	BRL/ARRADCOM, US, Private Communication, November 1980.
2-103	Price, C. Juhasz, A.A.	*A Versatile User-Oriented Closed Bomb Data Reduction Program (CBRED),* BRL Report No. 2018, September 1977, AD A049465.
2-104	Hussard, M. Paulin, J.L. Stephan, M.	*Fonctionnément des charges propulsives monoblocs en poudre agglomérée,* 5ème Symposium International de Balistique, Toulouse avril 1980.
2-105	–	Diehl, Ge, Private Communication, November 1980.
2-106	De Luca, L.	Istituto di Macchine, Politecnico di Milano, Italy, Private Communication, November 1980.
2-107	De Luca, L.	*Solid Propellant Ignition and Other Unsteady Combustion Phenomena Induced by Radiation,* Ph.D. Thesis, Dept. Aerospace and Mechanical Sciences, Princeton University, AMS Report No 1192-T, November 1976.
2-108	De Luca, L. Coghe, A. Reggiori, A.	*The Dynamics of Solid Propellant Combustion,* 1-st Annual Technical Report European Research Office, November 1978.
2-109	De Luca, L. Galfetti, L. Zanotti, C.	*Ignition and Extinction of Solid Rocket Propellants,* 53-rd Meeting AGARD-PEP on Solid Rocket Motor Technology, Oslo, Norway, April 1979.
2-110	De Luca, L.	*Instability of Heterogeneous Deflagration Waves,* VI Int. Symposium on Detonation, San Diego, US, August 1976.
2-111	De Luca L. et al.	*Radiative Ignition of Double Base Propellants: I – Some Formulation Effects,* AIAA Journal, Volume 14, No 7, July 1976, pp. 940-946.
2-112	De Luca L. et al.	*Radiative Ignition of Double Base Propellants: II – Preignition Events and Source Effects,* AIAA Journal, Volume 14, No. 8, August 1976, pp. 1111-1117.
2-113	Irish, C.G.	NAVORDSTA, Indian Head, US, Private Communication, November 1980.

2.2.3 Gaseous and Multiphase Flow in the Tube

This section is concerned with the experimental techniques which are presently used or developed for measuring the state and flow variables inside a gun tube as well as the heat transfer to the barrel. The efforts mentioned in the following have been made with the double objectives of: 1) obtaining input data for the gas dynamic models and 2) verifying the computed results. Additional input data should be available from the investigations which are related to section 2.2.1 ("Ignition Processes in the Weapon"), section 2.2.2 ("Inflammation and Burning"), chapter 4 ("Related Theory") and chapter 5 ("Specific Problems in Interior Ballistics").

This section is based on 27 inputs received from France, Germany, Italy, the United Kingdom and the United States.

It can be assumed that the content of the inputs does not cover all activities in this field. The contributions submitted can be expected, however, to present a general review on the activities concerned. The latter have either come to an end, or will be continued or are still in a phase of planning.

In a few cases precise information is excluded because of incomplete descriptions or lack of references.

Corresponding to the inputs received, the investigations can be classified, as follows, according to the physical variable which has to be measured:

- Pressure measurements in the clarinet tube,
- Pressure measurements at the base of the projectile and acceleration measurements onboard the projectile,
- Temperature and velocity of the powder gases,
- Velocity and distribution of the solid-state particles,
- Measurement of heat transfer to the tube,
- Measurement of axial projectile motion,
- Gas leakage,
- Special program for measurements.

2.2.3.1 Pressure Measurements in the Clarinet-Tube

References 2-114 to 2-121 are concerned with pressure measurements performed simultaneously in the chamber and along the tube. For this purpose mainly piezoelectric pressure transducers are used which are located in the wall of the tube. Because of the numerous holes needed for this kind of pressure measurement, and because of their distribution along the tube, such a tube is called clarinet tube. There exists no restriction for the caliber. Besides, strain gages are sometimes employed (Ref. 2-121).

The measured analog signals are recorded on magnetic tape recorders or are immediately digitized by means of transient recorders. At present the pressure transducers are usually calibrated up to 750 MPa by static procedures. However, dynamic calibration is necessary and is under development. Although pressure measurements belong to the conventional experimental techniques, some problems are still encountered in selecting and inserting the gages as well as in interpreting pressure oscillations. For measuring the spatial pressure distribution up to 18 transducers are placed along the tube (Refs 2-114 to 2-120).

Knowing the time-dependent spatial pressure distribution it is possible to elucidate the influence on the interior ballistic cycle of some important parameters such as projectile mass, propellant mass, shape of propellant grain, propellant temperature and charge design. A partial verification of the gas dynamic models is given by such pressure measurements. In order to determine the base pressure by pressure measurements along the tube, the pressure rise recorded by the gages must be analyzed exactly.

The determination of the friction force between projectile and tube wall by means of pressure measurements in the clarinet tube and the measurement of the projectile velocity for the same shot, as is reported in Reference 2-120, may lead to difficulties because of the measuring accuracy which seems to be insufficient for this problem.

2.2.3.2 Pressure Measurements at the Base of the Projectile and Acceleration Measurements Onboard the Projectile

Pressure measurements made at the base of the projectile are treated in References 2-122 to 2-131. The investigations in this field are still in their initial phase and are applied to guns of 20 to 203 mm in caliber. For data transmission out of the tube the well-known hard wire technique is used. In this case one wire or more are drawn from the tip of the projectile out of the muzzle to the recorder. The tip is formed like a cone or a cup for collecting the wire during the projectile motion. This technique is successfully used for low and medium projectile velocities.

The main problem to be found for base pressure measurements is concerned with the development of transducers which are suited for the high accelerations in the range of 50.000 g to 100.000 g and which must be acceleration compensated. Inductive sensors, piezoresistive carbon gages, strain gages, and piezoelectric pressure gages are under development and/or are tested in view of their applicability. In Reference 2-131 the development of a special large face transducer is presented which combines a quartz load washer with a relatively rigid tough thin diaphragm for recording gas and solid phase loading force effects.

Besides the hard wire technique, data transmission by microwaves is proposed. This technique is used in References 2-132 to 2-134 for testing the ammunition of large caliber weapons. Another method allows recording of the in-bore data which are transmitted to the ground station after the projectile has left the muzzle (Ref. 2-135).

As projectile motion inside the barrel is not controlled by base pressure only, additional measurements of axial and radial acceleration of the projectile are attempted in many cases. Inductive and piezoelectric accelerometers as well as strain gages are under development and/or are tested for their applicability. Difficulties arise for the radial acceleration measurements since the projectile is simultaneously subjected to axial acceleration which is two orders of magnitude larger.

Direct measurements of base pressure can contribute to answering the question: How far can pressure measurements in the clarinet tube be used in order to determine the gas pressure at the base? Larger caliber ammunition allows for housing more than one pressure gage in the base of the projectile, consequently pressure differences across the cross-sectional area can be measured. These measurements give the basis for a more exact test of the theoretical models, especially as far as the multi-dimensional models are concerned. The intended measurements of both the axial and radial acceleration are expected to reveal the load to which the projectile is subjected during the shot. In connection to subtitle 2.2.3.6 where remarks can be found concerning the measurement of the axial projectile motion, some aspects of interaction between projectile and tube wall can be investigated. Results for extraction resistance, engraving force and friction forces under dynamic conditions are expected which are important input data for the models.

2.2.3.3 Temperature and Velocity of the Powder Gases

Temperature and velocity of the powder gases, together with gas pressure, are among the most important state and flow variables needed for the verification of the models. Whereas the experiments of Reference 2-136 are limited to the flow field associated with a burning solid rocket propellant, optical techniques for measuring temperature and flow velocity inside the gun tube are described in References 2-137 to 2-149. These investigations were carried out by firing caliber 20 mm guns, the tube wall of which is equipped with special windows.

Emission-absorption spectroscopy is used for measuring the gas temperature including effects caused by the flow-borne powder particles and by the contamination of the inner tube wall. Axial temperature-time profiles were measured using this technique. Spectroscopic measurements of the radial temperature distribution have also been attempted. However, how far the limitations imposed by the high absorptivity of the in-bore flow can be overcome have not yet been decided (Ref. 2-150).

For measuring the flow velocity, a new type of laser-doppler velocimeter based on the principle of the Michelson-interferometer seems to be best suited. First experiments have been achieved for the axial and radial profiles of the axial velocity component. The spatial resolution of this technique does not allow, however, for the resolution of the boundary layer. Another technique for measuring the axial velocity component is based on the use of streak-camera recordings.

The techniques used in References 2-136 to 2-149 for measuring temperature and flow velocity of the powder gases yield encouraging results. However, further improvements are required to obtain experimental results which are sufficient for verifying the gas dynamic models.

2.2.3.4 Velocity and Distribution of the Solid State Particles

Measurements of velocity and local distribution of partially burned solid powder grains is treated in References 2-151 to 2-154. This technique makes use of a special 20 mm tube made from glass or organic fiber reinforced plastics transparent to x-rays. Form, local distribution and velocity of partially burned grains inside the chamber and the tube are visualized by means of high speed x-ray photography. The burning process inside the powder bed is analysed after ignition, before, and after the projectile starts to move.

These ongoing investigations have contributed to the knowledge about the powder grain motion which must be taken into consideration in the 2-phase flow models. The device is limited to a maximum allowable pressure loading of 350 MPa at present.

Similar experiments were conducted for a translucent cartridge case of a 5-inch gun (References 2-155 to 2-157). These investigations were limited however to the process of propellant ignition.

2.2.3.5 Measurement of Heat Transfer to the Tube

In References 2-158 to 2-167 temperature measurements in the tube wall are used for experimentally determining the heat input at the wall. In References 2-158 to 2-160 the early applications of calorimeters are mentioned.

These investigations are applied to guns of caliber 20 to 203 mm. Special high frequency response thermocouples are used. They are fitted into the wall along the tube with a residual distance from the inner bore surface of typically 1 mm to 10 μm. Different data reduction procedures are described in order to evaluate the total heat input to the barrel or the heat input as a function of time during the firing of a shot by means of solving the heat conduction equation. The measurement of the temperature profile across the barrel wall allows derivation of the temperature at the inner bore surface (cf. sections 2.1.2.1 and 2.1.3.3).

Measurements of inbore temperatures are carried out in order to evaluate the temperature of the inner bore surface and the heat input to the wall. Conclusions are expected for barrel wear, e.g. the effects of wear reducing additives. In combination with the measurements of the gas temperature, the heat transfer between propellant gases and barrel wall characterized by the heat transfer coefficient and the cook-off might be analysed.

2.2.3.6 Measurement of Axial Projectile Motion

The investigation of the axial projectile motion in the tube consists in measuring the distance covered, velocity or acceleration as a function of time. In subtitle 2.2.3.2 the measurements of acceleration were treated since they are connected with pressure measurements at the base because of the coherent problem formulation and data transmission.

References 2-168 to 2-173 are concerned with distance and velocity measurements. The microwave-interferometer with constant frequency is used as a standard technique for each calibre (see e.g. Refs 2-173 and 2-132 to 2-134). As a first disadvantage it must be mentioned that the spatial resolution of this technique is not sufficient for recording the initial phase of the projectile motion and is not accurate enough for an evaluation of resistive forces such as extraction resistance and engraving force in combination with pressure measurements. Additionally, the received doppler frequency which is proportional to the projectile velocity is not measured directly. This means that the signals result in a travel-time measurement. The projectile acceleration must be calculated by differentiating twice. The accuracy may suffer from this mathematical procedure.

Novel techniques for a more accurate resolution of the initial motion are proposed in References 2-168 to 2-173. In References 2-168 to 2-170 a microwave interferometer with dynamically adjusted frequency is described which leads to a resolution of the initial motion higher than that obtained with the standard microwave interferometer using constant frequency.

A resolution just as high is stated in Reference 2-171 for a laser-doppler interferometer. The laser-doppler velocimeter (Ref. 2-172) based on the principle of the Michelson-interferometer allows, depending on the operational conditions, either a high spatial resolution of the initial projectile motion or a medium resolution of the whole, in-bore motion. Since the signals are proportional to the velocity one differentiation is necessary for obtaining the acceleration values. Similar to other techniques using optical beams which are directed into the tube from the muzzle and/or emitted out of the tube, falsifications of the measured velocity variation may occur due to the leakage of the propellant gases past the moving projectile.

A third technique for a direct velocity measurement is reported in Reference 2-173. A CO_2 laser doppler is used for the first few centimetres and a 10 GHz microwave doppler for the rest of the in-bore travel. The measurements are tested on 40 mm and 105 mm guns.

Summarizing, the measurements of travel and velocity of projectile have reached a high level of reliability and accuracy. Together with the pressure measurements in the chamber and in the clarinet tube they are the most trustworthy measurements.

2.2.3.7 Gas Leakage

No references are available for this problem. Gas leakage may cause disturbances for some optical techniques. Investigations in this field should be encouraged since they are related to wear problems and the multi-dimensional gas dynamic calculation of the flow near the corner where the base of the projectile is in contact with the barrel wall.

2.2.3.8 Special Programs for Measurements

References 2-132 to 2-134 and 2-174 to 2-180 refer to special programs which consider a number of measurements carried out simultaneously on a single shot. In References 2-132 to 2-134 an interior ballistic test procedure for conventional high performance guns is described. These measurements include pressure measurement at breech, measurements of axial projectile motion by means of microwave interferometry, and measurement of base pressure combined with passive data transmission by microwaves. Reduction of data is done on the basis of a conventional lumped parameter model of interior ballistics. Consequently a survey on the spatial mean values of the essential interior ballistics quantities is available. The interaction between projectile and tube is treated in Reference 2-174. A complex and expensive experimental program was developed. Current efforts are directed to establish an algorithm for computing the spatial and temporal loads which act on the inner bore surface and are caused by the in-bore environment. In a later stage, emphasis will be on determination of what physical parameters are required and/or available for the computational simulation of the interior ballistics with multi-dimensional, 2-phase computer codes.

The basic purpose of the research program in References 2-175 to 2-180 is the determination of the primary, dominant mechanisms of hot gas flow erosion of exposed solid material surfaces and systematic identification of the critical mechanism followed by analysis of how the various mechanisms work together. The main goal of this extensive study is directed towards gun barrel erosion. On the basis of experimental results an interior ballistics model is developed for elucidating erosion processes under changing conditions, including non-steady and multi-dimensional influences, boundary layer effects, gas-borne particulate effects etc. These investigations may deliver a number of novel aspects for modeling the interior ballistic phenomena.

2.2.3.9 Conclusions

The efforts reviewed in this section are connected directly to the topics of the other chapters. The conclusions are:

- Measurements of gas pressure and projectile motion inside the tube are standard techniques. They arrived at a high level of reliability and accuracy except for the measurement of the initial projectile motion.
- Measurements of temperature in the tube wall are carried out without serious problems. Mainly, they are used for measuring the influence of erosion suppressing additives and are rarely focused on the physical problem of heat transfer from the propellant gas to the tube wall.
- Techniques for measuring the base pressure as well as the axial and radial acceleration of projectile are advanced with emphasis. The problems to be solved concern both data transmission and development of suitable transducers.
- Measurements of temperature and velocity of the powder gases as well as of velocity and distribution of the powder grains are encouraging. The velocity and distribution of the powder grains can be measured at a high level of reliability and accuracy, however, these measurements are limited to x-ray transparent tubes which do not allow for pressures as high as those occurring in modern high performance weapons. The measurements of temperature and velocity of the powder gases are in an early stage and need some improvement. The quantities made available by these measurements are very important for verifying one- and multi-dimensional theoretical models. Further efforts should be supported.
- The experimental verification of modelling secondary effects which are of less importance to the interior ballistics performance but have considerable influence on particular phenomena, such as the boundary layer for erosion processes, cannot be expected in the near future. Simulators in interior ballistics, which are operated by optically

transparent driver gases, are expected to offer advantages in the present case. Several laboratories have initiated the first preliminary experiments.

Concluding the section devoted to experimental techniques supporting theoretical model calculations, most of the essential experimental problems are attacked. Predominantly, measurements of a single quantity are carried out. More programs for simultaneously measuring several quantities for a single shot using recently developed techniques are necessary in order to understand and to model in a more realistic way the high speed non-steady processes of interior ballistics.

REFERENCES

2-114 Avilès, A., Clappier, G. — *Exhaustive Experimentation upon Internal Ballistics of Large Caliber Gun.* Proceedings Third International Symposium on Ballistics, Karlsruhe, BRD, 23-25 March 1977.

2-115 Fourre — *Détermination de coefficient d'influence de l'accélération axiale sur les capteurs de pression (KISTLER et PCB).* ETBS, France, PVI MET 1524, 1977.

2-116 Martinez — *Etude des ondes stationaires dans les tubes de calibres 5.56 – 7.62 et 9 mm.* ETBS, France, PVI MET 1528, 1977.

2-117 Fourre — *Réception de la chaîne TRISTAN.* ETBS, France, PVI MET 1504.

2-118 Simeon, B — *Estimation de l'influence de la température sur les capteurs piezoélectriques,* ETBS, France, PVI MET 1649, 1978.

2-119 Zimmermann, K. — *Untersuchung des Gasdruckverlaufs im Klarinettenrohr,* ISL Report PU 306/77.

2-120 Jasper, D. — *Examination of the Friction Between the Projectile and the Tube in a 27 mm Clarinet Tube,* Erprobungsstelle 91 (ErpSt 91), Meppen, FRG, Private Communication, 1979.

2-121 Bubb, G. — *Pressure Movement,* LCWSL, Dover, NJ, USA, Private Communication, 1979.

2-122 Desroches — *Essais d'adaption de la méthode de transmission par fil pendant la phase canon, à une arme de 120 mm lisse,* ETBS, France, PVI MET 1550, 1977.

2-123 Desroches — *Essai d'adaption de la méthode de transmission par fil pendant la phase canon, à une arme de 120 mm lisse: transmission d'une fréquence,* ETBS, France, PVI MET 1588, 1978.

2-124 Desroches — *Télémesure par fil de la pression culot. Essais de transmission d'une fréquence modulée par le signal d'un capteur embarqué en 120 mm lisse,* ETBS, France, PVI MET 1647, 1979.

2-125 Schultze, G., Zimmermann, K. — *Measurement of Pressures at the Base of Projectile as well as of Axial and Radial Accelerations,* Deutsch-Französisches Forschungsinstitut Saint-Louis (ISL), France, Private Communication, 1979.

2-126 Grumann, H., Gütlin, E., Zimmermann, G. — *Experimental Techniques for the Measurement of Case Extraction and Engraving Resistances for Small Caliber Projectiles,* Proceedings Fifth International Symposium on Ballistics, Toulouse, France, 16 – 18 April 1980.

2-127 Zimmermann, G. — (EMI-AFB) *Verfahren zur Messung des Geschossauszieh-und Einpresswiderstandes bei kleinkalibrigen Waffen,* Paper presented at 4. Symposium *Innenballistische Leistungssteigerung von Rohrwaffen,* Pfinztal-Berghausen, FRG, 29 November – 1 December 1978.

2-128 Grumann, H., Gütlin, E., Zimmermann, G. — (EMI-AFB) *Neuere Ergebnisse bei der Messung des Geschossausziehund Einpresswiderstandes,* Paper presented at 5. Symposium *Innenballistische Leistungssteigerung der Rohrwaffen,* Swisttal-Heimerzheim, FRG, 10 – 12 December 1979.

2-129 Bubb, G. — *Pressure Measurement at Base of Projectile,* LCWSL, Dover, NJ, USA, Private Communication, 1979.

2-130 Bubb, G. — *Measurement of Axial Projectile Motion,* LCWSL, Dover, NJ, USA, Private Communication, 1979.

2-131	Wieland, M.S.	*Determination of Projectile Forcing Function,* NSWC Dahlgren, VA, USA, Private Communication, 1979.
2-132	Biele, J.	*Measurement of In-Bore Motion of Projectiles and Simultaneous Data Transmission from Built-In Sensors by means of Microwave Interferometry,* Proceedings Second International Symposium on Ballistics, Daytona Beach, 1976.
2-133	Biele, J.	*Kenndaten-Ermittlung in der modernen experimentellen Innenballistik der Rohrwaffen,* BMVg-FBWT 75-26, Bonn, 1975
2-134	Biele, J. Trame, B.	*Neuere Verfahren der innenballistischen Routine-Messtechnik der Rohrwaffen,* Bericht ErpSt 91-2, No 23/79, Meppen 1979 or to be published as BMVg-FBWT, Bonn 1980/81.
2-135	Donnally, W.	*A New In-Bore Data Aquisition Technique for Gun Tube/Projectile Dynamics,* Proc. of the 2nd Symp. on Gun Dynamics, 19 – 22 September 1978, Rensselaerville, NY.
2-136	Coghe, A. et al.	*Gas Phase Velocity Measurements in Solid Rocket Propellants by Laser Doppler Anemometry,* Paper presented at 58th AGARD Meeting, Symposium on Solid Rocket Motor Technology, Oslo, Norway, April 1979.
2-137	Mach, H. Masur, H. Werner, U.	*Verlauf der Pulvergastemperatur im Lauf eines Gasdruckmessers. Erste Messungen,* ISL-Report No R 109/76, 1976.
2-138	Klingenberg, G. Mach, H.	*Experimental Study of Non-Steady Phenomena Associated with the Combustion of Solid Gun Propellants,* Proceedings of the Sixteenth Symposium (International) on Combustion, The Combustion Institute, pp. 1194-1200 1976.
2-139	Heiser, R. Klingenberg, G. Mach, H.	*Theoretical and Experimental Determination of Flow Properties Inside the Tube of a Gun,* Proceedings Third International Symposium on Ballistics, Karlsruhe, FRG, March 23 – 25, 1977.
2-140	Klingenberg, G. Mach, H.	*In-Bore Measurements of Gas Velocity and of Radial Temperature Distributions,* Proceedings Fourth International Symposium on Ballistics, Monterey, CA, USA, October 17 – 19, 1978.
2-141	Klingenberg, G. Mach, H. Wieland, O.	*Spektroskopische Temperaturmessengen in der Pulvergasströmung vor der Mündung eines 20 mm Gasdruckmessers,* EMI-AFB-ISL-Report No R 136/76, 1976.
2-142	Mach, H. Werner, U. Masur, H.	*Untersuchungen an Pulveroszillationen im Lauf einer Maschinenkanone Kaliber 20 mm* ISL-Report No R 105/75, 1975.
2-143	Klingenberg, G. et al.	*Spektroskopische Temperaturmessungen in der Pulvergasströmung im Laug und an der Mündung einer Maschinenkanone Kaliber 20 mm.* EMI-AFB-ISL-Report No R 106/77, 1977.
2-144	Klingenberg, G. Wieland, O.	*Untersuchungen der Eigenschaften von vier Experimentier-Treibladungsanzündern beim Abfeuern in den freien Raum,* EMI-AFB-Report, in print.
2-145	Smeets, G. George, A.	*Instantaneous Laser Doppler Velocimeter Using a Fast Wavelength Tracking Michelson Interferometer,* Rev. Sci. Instrum. Volume 49, No 11, 1589-1596, November 1978.
2-146	Mach, H. Werner, U. Smeets, G.	*Beitrag zur optischen Untersuchung von Treibladungsanzündern,* ISL-Report R 107/79, 1979.
2-147	Mach, H. Smeets, G. Klingenberg, G.	*Geschwindigkeitsmessungen in instationären Strömungen mittels eines Laser-Interferenz-Velocimeters,* ISL-Report CO 204/78, 1978.
2-148	Klingenberg, G. Schröder, G.A.	*Investigation of Combustion Phenomena Associated with the Flow of Hot Propellant Gases II: Gas Velocity Measurements by Laser-Induced Gas Breakdown,* Journal Combustion and Flame, 27, 177-187, 1976.

2-149 Klingenberg, G.
Mach, H.
Smeets, G.
Gas Velocity Measurements within Reactive Propellant Gas Flows, AIAA-Journal, to be published.

2-150 Mach, H.
Klingenberg, G.
Gegenwärtiger Stand der Gastemperaturmessungen im Waffenrohr. Beitrag zur Messmethode von radialen Temperaturverteilungen, ISL-Report CO 223/79, 1979.

2-151 Schröder, G.A.
Hornemann, U.
Visualisation of Combustion and Flow Phenomena in Interior Ballistics, Proceedings Second International Symposium on Ballistics, Daytona Beach, USA, March 1976.

2-152 Hornemann, U.
Investigation of Propellant Combustion in X-Ray Transparent Gun Tubes, Fourth International Symposium on Ballistics, Monterey, USA, October 1978.

2-153 Hornemann, U.
An Investigation of Propellant Combustion in X-Ray Transparent Gun Tubes, EMI-AFB-Report 3/79, 1979.

2-154 Hornemann, U.
Visualisation of Propellant Gas Flow Inside a Gun Barrel, Paper presented at Second International Symposium on Flow Visualisation, Bochum, FRG, September 1980.

2-155 Soper, W.G.
Ignition Waves in PYRO Propellant, Combustion and Flame, Volume 20, April 1973, p. 273-276

2-156 Soper, W.G.
Ignition Waves Gun Chambers, Combustion and Flame, Volume 20, April 1973, p. 157-162

2-157 Soper, W.G.
Grain Velocities During Ignition of Gun Propellant, Combustion and Flame, Volume 24, February 1975, p. 199-202.

2-158 Fourre
Températures élevées rapidement variables – Etudes preliminaire, ETBS, France, PV1 MET 1614, 1978.

2-159 Simeon, B.
Mesure des températures rapidement variables dans un canon clarinette de 121, 4 mm, ETBS, France, PV1 MET 1630.

2-160 Prévot, P.
Soulages, M.
Contribution à la modélisation des pertes thermiques dans les tubes d'armes par une méthode numérique appliquée au phenomène de convection forcée. Rapport Nr. 1. ETBS, Note Technique 2/CT/CdB/79, 1979.

2-161 Zimmermann, K.
et al.
Der Wärmeübergang in Rohrwaffen, ISL-Report, RT 506/78, 1978.

2-162 Guse, P.
Bestimmung der Temperaturverteilung in Waffenrohren während der Schussentwicklung, Proceedings Third International Symposium on Ballistics, Karlsruhe, FRG, March 1977.

2-163 Standen, P.
Barrel Heating, Heat Transfer to Barrel, GR1/RARDE, UK, Private Communication, 1979.

2-164 Vassalo, R.A.
Mathematical Models and Computer Routines Used in Evaluation of Caseless Ammunition Heat Transfer, Calspan Report No GM-2948-Z-1, June 1971.

2-165 Hirschfelder, J.O.
et al.
Heat Conduction, Gas Flow and Heat Transfer in Guns, National Defense Research Committee Report No A-87, August 1942.

2-166 Vassallo, F.A.
Heat Transfer and Erosion in the ARES 75 mm High Velocity Cannon. Calspan Technical Report No VL-5645-D-1, October 1975

2-167 Lader, S.
Russel, K.
Measurement of Wear and Heat Input in the 105 mm Cartridge TP-T-M490 Using M68 Gun. USA ARRADCOM, Large Caliber Weapons System Laboratory, Dover, NJ.

2-168 Schröder, G.A.
et al.
Untersuchung der Auswirkung von Störungen und Unsymmetrien bei An-und Abbrand von Treibladungen auf des Geschossverhalten in und vor dem Waffenrohr. Paper presented at 3rd Symposium *Inneballistische Leistungssteigerung der Rohrwaffen* Weil am Rhein, FRG, 22 – 24 November 1977.

2-169 Schröder, G.A. et al. *Untersuchung der Auswirkung von Störungen und Unsymmetrien bei An-und Abbrand von Treibladungen auf das Geschossverhalten in und vor dem Waffenrohr.* Paper presented at 4th Symposium *Innenballistische Leistungssteigerung der Rohrwaffen,* Pfinztal-Berghausen, FRG, 29 November – 1 December 1978.

2-170 Grumann, H. (EMI-AFB) *Experimentelle Verfahren zur Untersuchung des innenballistischen Geschossverhaltens.* Paper presented at *Abgangsballistik und Treffwahrscheinlichkeit,* Course of the Carl-Cranz-Gesellschaft, Weil am Rhein, 5 – 9 May 1980.

2-171 Hühn, R. *Measurement of the Projectile Velocity in a Gun Tube Using Laser-Doppler-Velocimetry Including a Michelson Interferometer,* Deutsch-Französisches Forschungsinstitut Saint-Louis (ISL), France, Private Communication, 1979.

2-172 Smeets, G. George, A. *Laser-Doppler-Velocimetrie mit Hilfe eines Michelson-Interferometers mit schneller Phasennachführung.* ISL Report No. R 124/78, 1978.

2-173 Fuller, P.W. *Measurement of Axial Projectile Motion,* GR2/RARDE, Fort Halstead, UK, Private Communication, 1979.

2-174 Loder, R.K. Elder, A.S. *Projectile-Gun Tube Interactions.* BRL-Report No. 1949, December, 1976.

2-175 Buckingham, A.C. *Wind Tunnel Wall Coating by Liquid Droplets Injected in High Intensity Turbulent Gas Flow.* Multiphase Flows and ARO Workshop, eds. J. Chandra, C.K. Zoltani, February 1 – 2, 1978, p. 129 and Lawrence Livermore Laboratory UCRL-80843, 1978.

2-176 Buckingham, A.C. *Numerical Simulations of Reactive Turbulent Gas Flows.* AIAA Paper 78-1143, AIAA 11th Fluid and Plasma Dynamics Conference, Seattle, Washington, July 10 – 12, 1978 and Lawrence Livermore Laboratory UCRL-81175, June 1978.

2-177 Buckingham, A.C. Magee, J.P. *NESTBDF: Nonequilibrium Streamtube Flow Calculations with Backward Differentiation Formula Integration Algorithm.* Lawrence Livermore Laboratory UCRL-52564, August 1978.

2-178 Buckingham, A.C. *Propellant Driven Turbulent Interior Ballistics and Wall Erosion.* AIAA Paper 79-007, AIAA 17th Aerospace Sciences Meeting, New Orleans, LA, January 15 – 17, 1979 and Lawrence Livermore Laboratory UCRL-81289.

2-179 Buckingham, A.C. Kang, S.W. *Multi-Dimensional Interior Ballistics Computations on Wear and Erosion Mechanisms in Gun Barrels,* in Proc. 1979 JANNAF-CPIA Propulsion Conference, Anaheim, CA, March 6 – 8, 1979, and Lawrence Livermore Laboratory UCRL-81649, December 1978.

2-180 Buckingham, A.C. *Turbulent Dusty Gas Motions with Weak Statistical Coupling.* AIAA Paper 79-1484 AIAA 12th Fluid and Plasma Dynamics Conference, Williamsburg, VA, July 23 – 25, 1979.

Chapter 3

RELATED FLOW PHENOMENA

3.0 INTRODUCTION

In this chapter we are concerned with analysing and observing phenomena associated with the main interior ballistics area discussed in the previous chapters. One of the most predominant aspects considered in this respect appears to be that of gas outflow from rockets, tube launchers, recoilless and conventional guns. There are, however, contributions dealing with the effects of chamber rotation on interior ballistics as well as sabot discard, to mention some of the more usual problems in this area. The scope of the contributions suggests that they be discussed in the following way:

(a) Outflow problems. (b) Other related flow problems.

The first of these sections will be discussed conveniently under the subheadings of:

(i) Experimental Programs. (ii) Theoretical considerations.

It is impossible to restrict ourselves to citing only the published work as many of the contributions are in the early stages of conception. We therefore mention at least once each of the contributors to this chapter in the hope that by the time this document comes to issue, other published work may have appeared in the open literature.

3.1 OUTFLOW PROBLEMS

Most of the cited 38 references deal directly with or are related to the outflow of gases from a tube launcher. In this section we consider the first of these, categorising the contributions into the two further areas of venting at the muzzle and venturi respectively. In recoilless weapons both regimes are evident whereas in conventional guns and rockets only the one is apparent.

3.1.1 Experimental Programs

The classical problem of investigating experimentally the chemical and physical processes occurring in the muzzle blast field of guns and tube launchers have been studied at length by Klingenberg (Refs 3-23 to 3-25). Also Schmidt (Ref.3-35) and Pennelegion and Grimshaw (Refs 3-18, 3-19), Trinks and Schlift (Ref.3-38) have published contributions in this area. A technique common to all researchers for the investigation of the growth of temporal and spatial blast fields as well as the identification of shock is the use of spark shadowgraph photography. Shadowgraph and Schlieren methods are well established and widely used for this purpose. See Refs 3-18, 3-23 and 3-35 for sample configurations.

Specifically, (Refs 3-23 to 3-30) and (Ref.3-38) are primarily concerned with the coupled effects of muzzle field flow and the combustion phenomena that occurs in it. The multiple reignition of combustible constituents in the emerging gases and the way this affects the flow variables have been considered. The development of the precursor flow fields and shock waves are considered important in as much as they initialise the environment for the oncoming propellant gas flow regime. The precursor, consequently, has received much attention in the above listed references. Measurement of flow velocity of the gas flow field has been done in (Ref.3-27). Use of standard techniques such as mechanical probes and laser anemometry are unacceptable on the grounds that they actually interfere with the flow, as in the former case, or that they are hampered by contamination in the gases, as in the latter. A new technique is discussed in (Ref.3-27) to overcome this problem and suggests a method of illuminating the gas by laser-induced gas breakdown. A temperature measuring technique for the muzzle flow field is described in (Ref.3-25). In this reference, as well as in (Ref.3-38), the effects of venting into different outside environments of pressure and/or gas constituents are considered.

By contrast (Refs 3-28, 3-19) report on the blast field resulting from the use of different ejection gases through a range of conical nozzles. The temporal growth of the blast front in this was measured by an image converter camera (IMACON) capable of high framing rates, as well as with the usual Schlieren methods. Times of arrival and peak overpressures were measured using an array of miniature Piezo-electric side-on blast pressure gauges. Driver gas parameters were found to be far more influential than the effects of the nozzle divergence angle for the cases considered.

With the exception of (Refs 3-18, 3-19) the above references are dealing specifically with flow at the muzzle. Other work is in progress considering the interference of the muzzle and venturi flow fields for the case of recoilless launchers.

For the venturi problem in particular, blast levels and noise reduction are prevalent studies in regards to, among other things, operator safety. To this end research is underway (Ref.3-10) to improve the quality of shadowgraph photographs. A parametric study involving variation of diaphragm bursting pressure, motor volume and weight of nozzle enclosure was conducted on shoulder fired rockets and RCL guns with the intention of minimising the blast overpressure at the operator's ear (Ref.3-13). A similar study is considered using on board instrumentation of rockets in (Ref.3-12). A further parametric study is underway giving attention to the bursting pressure of the diaphragm and expansion of the launcher tube (Ref.3-8). The attenuation of noise and blast is also discussed for volleys as well as single shots in the work of (Ref.3-11).

3.1.2 Theoretical Considerations

The mathematical modelling of blast flow fields in the vicinity of nozzles is a formidable task. The essentially three dimensional nature of the flow, presence of shock discontinuities and particle interference are just some of the features which require particular attention. Numerical prediction of the flow variables is usually based on some kind of finite difference technique although there is a case (Ref.3-38) where finite element schemes have been used for special problems. Codes which perform these computations are mentioned in (Refs 3-9, 3-14 to 3-16, 3-20, 3-22, 3-32). Both Lagrangian (travelling frame of reference) and Eulerian (fixed frame of reference) formulations have been used as a basis for these codes. Also several different algorithms are mentioned in serving to extract the flow variables at each time step. We note in particular that (Ref.3-20) and (Ref.3-32) have adopted the method of characteristics to solve the set of equations in two space variables. Other authors (Refs 3-4, 3-14 to 3-16, 3-22) have adopted a fluid-in-cell approach. In particular, the code used in (Refs 3-14, 3-15) is a three dimensional formulation. This "implicit" scheme marches in time by using a combination of iterative methods (Jacobi point by point) and simultaneous solution (Alternating Direction Implicit Method). This code has also a two phase capability and has been used to study chemically reacting turbulent flow in a blast field.

The objectives and implementations of these codes are somewhat diverse. We summarize them as follows.

In investigating sound levels in relation to safety limits Soo Hoo, (Ref.3-9) has developed an integrated system of three codes in order to predict the rocket motor blast field around a tube launcher. Firstly, an interior ballistics model describing the rocket motor performance parameters establishes a data base for the ensuing motion. Additionally, a second code based on a one dimensional Lagrange formulation, describes the transient flow phenomena like shock front formation. These provide the data base at the nozzle exit plane for the main two dimensional axisymmetric hydrocode which computes the blast field. Excellent agreement with experiment was found provided the nozzle exit plane parameters in the two cases were forcibly matched.

The method described in (Ref.3-20) and (Ref.3-32) also feature the determination of shock waves. The former has been used successfully with exit to ambient pressure ratios of the order of 10^5. The latter has been developed more specifically to study the flow about the projectile in the blast field.

In the treatment of turbulent multiphase flow (Refs 3-14, 3-15 and 3-22) have reported good agreement with experimental trials. It is interesting to note that three dimensional asymmetric flow has already been considered by this group. Presently they are extending the axisymmetric flow problem in nozzles to consider further influences on the motion like that of particle velocity and thermal lags.

The authors of (Ref.3-16) have specifically developed an axisymmetric two dimensional model to examine the blast field effects of a shoulder fired LAW. In this report the fluid-in-cell method (FLIC) of solution is compared to an Eulerian code PISCES for a specific test case. The three regimes FLIC, PISCES and experiment appear to have good agreement in as far as magnitude of overpressures were concerned. As mentioned in (Ref.3-9), the rocket nozzle start process appears to be a very important parameter in that it dominates the ensuing blast evolution. This numerical type of model is also being developed and implemented in (Ref.3-4).

3.2 OTHER RELATED FLOW PROBLEMS

The feature most closely related to the classical outflow problem is that of assessing the performance of the projectile in this intermediate ballistic region. We review this major related area first.

A two dimensional axisymmetric unsteady flow hydrocode has been developed by Moore (Ref.3-6) to simulate the projectile environment during the muzzle blast flow. Good agreement has been made when comparing the predictions with the US Navy 5"/54 gun, US Army M-16 and 105 mm Howitzer.

Schmidt et al. (Refs 3-17, 3-33 to 3-37), have been concerned with the malign disturbances on the projectile as it passes through this region and later at sabot discard with the ultimate aim of reducing the effects on the dispersion of the projectile at the target. The dominant effects of aerodynamic interference and mechanical impingement are discussed at length. Tests with a 1/3 scale model of APDS were performed. Also, supporting theoretical analysis has been undertaken to assist in the overall program.

Bowman (Ref.3-1) has conducted experimental trials using a quasi-steady free jet impinging obliquely and parallel but off-line on a projectile base located within the jet shock bottle. Theoretical considerations include using blunt body aerodynamics with semi-empirically derived data for comparison with the above hypersonic gun tunnel test.

The scope of (Ref.3-2) is to develop methods of reducing blast by means of annular liquid sheets. Rectangular shock tubes are used for this purpose with water injected around the opening of the shock tube in the downstream direction.

A unique investigation is underway from theoretical and experimental points of view of examining the effects of a spinning combustion chamber on the interior ballistics of a gun (Ref.3-21). For spinning speeds between 1,000 and 8,000 rpm it has been found that any increase in rotation causes greater maximum thrust at shorter burning times. X-ray photographs of the burning surface show rotation influenced funnel shapes deepening in the grain near the centre-line.

With respect to aircraft mounted guns, a study is underway to determine the field variables around a gun muzzle in the vicinity of a surface (Ref.3-7). Both theoretical and experimental aspects are being considered.

In (Ref.3-8), the physiological aspects of blast overpressure are investigated by the exposure of monkeys and guinea pigs to the sound levels.

REFERENCES

3-1	Bowman, J.E.	RARDE, Private Communication.
3-2	East, R.A.	Southampton University, Private Communication.
3-3	Evans, J.R.	RARDE, Private Communication.
3-4	Hillier, R. Graham, J.M.R.	Imperial College, Private Communication.
3-5	James, D.J.	AWRE, Private Communication.
3-6	Moore, G.	NSWC, Private Communication.
3-7	Munt, R.M.	Ministry of Defence, Private Communication.
3-8	O.N.E.R.A.	Ministère de la Défense, Private Communication.
3-9	Soo Hoo, G.	NSWC, Private Communication.
3-10	Stollery, J.L.	Cranfield Institute of Technology, Private Communication.
3-11	Vigneras, M.	Ministère de la Défense, Private Communication.
3-12	Williams, G.J.	PERME, Private Communication.
3-13	Clayden, W.A. Hillman, A.	*Some Recent UK Work on Noise from Shoulder-Launched Recoilless Weapons*, 4th International Ballistics Symposium, Monterey, October 1978.
3-14	Cousins, J.M.	*Computer Programs to Calculate Chemically Reacting Flow in Axisymmetric Nozzles.* PERME TR 84 (1978).
3-15	Cousins, J.M.	*Prediction of Three-Dimensional Properties in a Rocket Exhaust Plume: The REP4 Computer Program.* PERME TR, to be published.
3-16	Edwards, D.G. Hillman, A.	*Computation of Rocket Blast Fields*, 5th International Symposium on Ballistics, Tolouse, Toulouse, 1980.
3-17	Gion, E.J. Schmidt, E.N.	*Measurements on a Circular Plate Immersed in Muzzle Flow*, BRL Report No.2762, June 1977.
3-18	Grimshaw, J.F. Pennelegion, L.	*A Parametric Study of Weak Blast Waves from Conical Nozzles Driven by Compressed Gases.* 4th International Ballistics Symposium, Monterey, October 1978.

3-19 Grimshaw, J.F.
Pennelegion, L.
The Simulation of Infantry Weapon Blast Using a Compressed Gas Source, Proc 6th Int Symp on Mil. Appl. of Blast Simulation, Cahors, France, 25–29 June 1979.

3-20 Hensel, D.
Ein Bicharakteristekenverfahren zur Berechnung stossbehafteter, instationärer Ausstromungen idealer Gase aus drehsymmetrischen Rohren. Dissertation, Aachen, 1976.

3-21 Jay, H.
Ernst, H.J.
Klein, H.
Rotationsstand zur Untersuchung des Abbrandverhaltens Schnell Drehender Treibsätze, ISL-RT 520/75.

3-22 Jensen, D.E.
Spelling, D.B.
Tatchell, D.G.
Wilson, A.S.
Combustion and Flame, 1979, 34, 309.

3-23 Klingenberg, G.
Investigation of Combustion Phenomena Associated with the Flow of Hot Propellant Gases. III: Experimental Survey of the Formation and Decay of Muzzle Flow Fields and of Pressure Measurements, Journal Combustion and Flame 29, p.289–209 (1977).

3-24 Klingenberg, G.
Experimentelle Untersuchungen zur Strömungs-Ausbildung vor der Mündung von Kleinkalibrigen Waffen, EMI-AFT-Rep. No. 1/75. (1975).

3-25 Klingenberg, G.
Mach, H.
Investigation of Combustion Phenomena Associated with the Flow of Hot Propellant Gases. I: Spectroscopic Temperature Measurements Inside the Muzzle Flash of a Rifle. Journal Combustion and Flame 27, 163–176 (1976).

3-26 Klingenberg, G.
Mach, H.
Experimental Study of Non-Steady Phenomena Associated with the Combustion of Solid Gun Propellants, Proceedings of the 16th Symposium (International) on Combustion, The Combustion Institute, pp. 1193–1200 (1976).

3-27 Klingenberg, G.
Schröder, G.A.
Investigation of Combustion Phenomena Associated with the Flow of Hot Propellant Gases. II: Gas Velocity Measurements by Laser-Induced Gas Breakdown, Journal Combustion and Flame 27, 177–187 (1976).

3-28 Klingenberg, G.
Mach, H.
Smeets, G.
Geschwindigkeitmessungen in Instationären Strömungen Mittels eines Laser-Doppler-Velocimeter, Vortragstext, Fruhjahrstagung der Deutschen-Physikalischen Gessellschaft, Fachausschusse Kurzzeitphysik, Munchen 6. 10.3.1979.

3-29 Klingenberg, G.
Analysis of Flow and Combustion Phenomena in Transitional Ballistics, EMI-AFB-Rep. No. E19/77 (1977).

3-30 Klingenberg, G.
Analysis of Gun Muzzle Flash Phenomena, 4th International Ballistics Symposium, Monterey, October 1978.

3-31 Mabey, D.G.
Capps, D.S.
Blast from Moving Guns, J. Aircraft 14 (1977), 687–692.

3-32 Mittelbach, P.
MBB-TN-RT332 9/77.

3-33 Schmidt, E.M.
Aerodynamic Interference During Sabot Discard, Workshop of Dynamics of Precision Gun Weapons, Rock Island, IL, January 1977.

3-34 Schmidt, E.M.
Shear, D.D.
Aerodynamic Interference During Sabot Discard, AIAA Atmospheric Flight Mechanics Conference, Hollywood, FL., August 1977, AIAA Paper 77–1158.

3-35 Schmidt, E.M.
Shear, D.D.
Optical Measurements of Muzzle Blast, AIAA Journal, Vol 13, No.2, August 1975, pp. 1086–1091.

3-36 Schmidt, E.M.
Gion, E.J.
Muzzle Blast from Guns, ADPA 2nd Energy Environment Conference, Kansas City, Missouri, March 1977.

3-37 Schmidt, E.M.
Fansler, K.S.
Shear, D.D.
Trajectory Perturbations of Fin-Stabilized Projectiles due to Muzzle Blast, Journal of Spacecraft and Rockets, Vol.14, No.6, June 1977.

3-38 Trinks, H.
Schilf, N.
Dynamische Analyse von Reaktionspartnern in Treibgasstromungen. Vortr. Symp.: Innenballistische Leistungssteigerung an Rohrwaffen – 1978.

Chapter 4

RELATED THEORY

Three NATO countries (United States, Germany, France) sent in eleven data sheets in reply to the request for information about work relating to equations of state; information provided on the kinetics of combustion and the combustion of propellants served as the basis for preparing this text.

4.1 EQUATIONS OF STATE OF GASES AND THERMODYNAMIC CALCULATIONS

A major problem in interior ballistics is calculating the muzzle velocity of the projectile and the pressure build-up in the weapon on the basis of the propellant loading characteristics. Calculating the pressure as a function of time requires an equation of state which is valid within the temperature and pressure range in question. Computing the thermochemical characteristics of the propellant gases is also possible only by using an equation of state, thus there is a dual requirement for a sufficiently precise equation of state directly usable in interior ballistics.

At the pressure levels customarily reached in weapons, the intermolecular forces contribute to the pressure behaviour of the gas to such an extent that one is led to use a real gas equation. The repulsion forces reflect the finite volume of the molecules while the attraction forces reflect the cohesion of the gas. Empirical equations of state have been proposed to express these qualitative notions and the best known is the Van der Waals equation.

Since, at high-pressures the attraction forces become negligible compared to the repulsion forces, ballistics experts have adopted the Noble-Abel equation which retains only the covolume term from the Van der Waals equation.

For very high-pressure applications, however, a more accurate equation of state is necessary. New equations with theoretical bases have therefore been developed based on statistical molecular mechanics which, with the customary notation, takes the general form:

$$z = \frac{P}{\rho RT} = \sum_{i=1}^{\infty} a_i \rho^{i-1} .$$

The terms with coefficients a_i $(i > 1)$ represent the deviation with respect to the perfect gas expression.

Calculating these coefficients requires taking account of the collisions between molecules and hence of the forces involved and, consequently, of the functions of intermolecular potentials.

Whereas, in the case of pure gases, the problem is comparatively simple, in the case of gas mixtures there is some difficulty in allowing for the interactions between molecules of different types (polar and non-polar) and in calculating the coefficients of the higher-order virial equation.

The work described below relates primarily to the application or improvement of equations of state of the virial type by seeking better-suited molecular interaction potentials, and also methods of calculating the coefficients in the case of gas mixtures. Since the equation of state proper and the calculation of the thermodynamic characteristics of the combustion gases are closely linked, both have been placed in the same paragraph.

4.1.1 Work in Progress

1. Research aimed at determining a precise equation of state for propellant gases is under way at ARRADCOM USA. (Ref.4-1; Ref.4-7).

   The thermodynamic characteristics of molecules of the same type as propellant gas molecules have been calculated by fixing the function for intermolecular potential.

   The equations of Percus Yevic, of Werlet and Weise and of Harr and Shenker have been applied using only the Lenard-Jones potential to compute the pressure in the case of nitrogen and the results are being compared with available experimental findings.

   The Percus Yevic equation turned out to be more accurate than the Werlet and Weise equation. An expansion of the Harr and Shenker virial equation gave good results when the second and third coefficients of the virial equation were precisely determined (an energy criterion was used to determine the hard-sphere diameter).

2. An experimental study of the equations of state is currently under way at the ISL (France/Germany) and is conducted by Grune.

   Tests in pressure vessels using different loading densities producing pressures between 300 and 700 MPa have shown that the Noble-Abel equation of state is not always valid beyond 400 MPa after correction has been made for heat losses. (Ref.4-8).

   Only propellants with an equalized oxygen balance obey this law perfectly. In the case of the others, the force and covolume are not constant, the latter decreasing at high pressures. This behaviour can be explained by different virial coefficients of the various parts of the combustion gases and, in particular, by the abnormal behaviour of water. Better agreement with the experimental findings was obtained by applying a virial equation.

   At the same time, a simplified analysis permitting determination of the virial coefficients from experimental findings has been proposed. These coefficients have been determined up to 500 MPa, and the computed and measured pressures are in good agreement (Ref.4-9, Ref.4-10).

3. A computer code for calculating the thermodynamic characteristics of propellant gases was prepared at ICT (Germany) by Volk and Bathelt. This code (Ref.4-11) uses the three-coefficient virial equation as the equation of state of the gases. The virial coefficients are calculated by means of the Lenard-Jones molecular interaction potential for polar molecules. The virial coefficients relating to the mixture are computed by the methods shown by Hirschfelder. Thermodynamic characteristics such as specific heat, number of moles, flame temperature, etc. are determined from classic expressions derived from the equation of state. The covolume is computed using the Noble-Abel equation. Good agreement between theoretical and experimental results was noted for a wide variety of propellants provided that consideration was given to the exact composition of the propellant (humidity, residual solvents, inorganic substances). At high pressure a comparative study reveals the influence of the formation of methane on the computed thermodynamic parameters. Further, an analysis of the combustion gases of a monopropellant reveals differences between the theoretical and experimental methane contents. This suggests that in this instance the assumption of balanced reactions is not valid and that it is necessary to take non equilibrium reactions into account (Ref.4-12).

4. A code (DETO-DEFLAG) for computing thermodynamic characteristics of propellants was prepared at the research centre at Le Bouchet (SNPE, France). This routine is based on a third-order virial equation and computes the thermodynamic parameters of constant volume combustion gases on the assumption that thermodynamic equilibrium has been achieved. In addition to the C, H, O and N components it also takes approximatively inorganic additives into account if their percentage contents are low. The virial coefficients are calculated using the Lenard-Jones and Stokmayer potentials for non-polar and polar molecules respectively. Agreement with closed-bomb experiments is to within about 5% with regard to pressure (without correction made for heat losses). (Ref.4-19). A second more comprehensive code that takes inorganic compounds fully into account is being prepared.

   Meanwhile a similar code, employing the Carnahan-Starling equation of state in conjunction with the Lenard-Jones potential was developed at ONERA in connection with work on a liquid-propellant gun so as to take account of the effects of real gases. A comparative study showed good agreement with the DETO-DEFLAG code for the C, H, O, N components (at pressures $P < 500$ MPa).

4.1.2 Future Work

1. Vladimiroff indicates that much of the future research work at ARRADCOM is dependent on the availability of accurate intermolecular potentials for propellant gas molecules. This information should soon be forthcoming from various experimental sources such as molecular beams and data on solids, as well as from direct ab initio calculations.

   Improving the equations of state would require taking into account the fact that certain molecules are not spherical and that consequently the theories should be extended to include at least dipole and quadripole interactions.

   It is planned to use a ballistic compressor to take some equation of state measurements directly. Spectroscopy would be used to measure temperature and density along with pressure measurements to determine the equation of state for propellant gases, individually and as mixtures.

2. Grune of the ISL intends to continue closed-bomb tests up to 1000 MPa to determine whether a more accurate equation of state up to the second virial coefficient is necessary beyond 500 MPa.

3. A code to calculate the thermodynamic characteristics of propellant gases as a function of time is to be established at ICT (Germany). It will be based on taking the non-equilibrium reactions into account (Ref.4-2).

4. The theoretical and experimental research will be continued at the Bouchet Research Centre in order to improve the predictability of the thermochemical characteristics of propellant gases at constant volume. On the basis of these results an attempt will be made to establish an equation of state of the Noble-Abel type in which the covolume and force parameters will depend on the pressure.

The ultimate objective is to obtain an accurate equation of state capable of easy manipulation that does not overburden interior ballistics computer code capability.

Out of this body of research two main courses have been charted for future research:

- Obtaining an accurate equation of state for propellant gases depends on determining the appropriate molecular interaction potentials, particularly by allowing for the fact that certain molecules are not spherical. Finally, investigation of mixtures of different types of gas molecules must be continued.
- A comparison between the experimental findings using a closed bomb, and the theoretical figures, is appropriate for judging the validity of an equation of state only if the computed composition of the gases is correct. Usually the composition of the gases is determined at constant volume on the assumption of thermodynamic equilibrium, but it would appear that in certain cases (cold propellants, monopropellants, ignition mixtures) this assumption, turns out not to hold, making it necessary to take non-equilibrium reactions into account.

4.2 COMBUSTION AND COMBUSTION KINETICS

The process of decomposition of the solid propellant to gas is essential because it affects the ignition phenomena and the way the pressure evolves; this through the combustion rate and the composition of the gases. The first stage is to establish a law which wholly expresses the combustion process for use in a ballistics model.

However, to understand certain anomalies in the combustion rate curves or to make advances in the quest for new propellants, it is useful to understand the elementary mechanisms of combustion and to be able to model them.

All the data sheets furnished by the various countries deal with these different aspects.

4.2.1 Ongoing Work

1. *Combustion rate.*

   A systematic investigation of the propellant combustion laws has been undertaken at SNPE (Le Bouchet Research Centre, France). (Ref.4-3). The purpose of this research is to make available experimental stationary combustion laws over the 10 to 600 MPa range, required to permit the construction of interior gun ballistics models. The measurements were made at +21°C and +51°C, both in the strand burner mode and in closed-bomb experiments. (Single and double base propellants). To facilitate utilization in ballistics models, a representation of burning rate in the form $aP + b$ or aP^n is effected systematically for each type of propellant in various pressure ranges and for the two temperatures. Taking the ignition phase into account in calculation models requires knowledge of the combustion law at very low pressure, an area where the effect of the non-steady state is extremely important.

2. *Combustion kinetics.*

   2.1. An investigation of the combustion kinetics of nitramine composite propellants is being carried out at the Air Force Armament Laboratory, by Powers (USA). (Ref.4-4). The objective of this work is to gain a better understanding of the thermal decomposition mechanism of hexogen (RDX), octogen (HMX) and triaminoguanidine nitrate (TAGN) so as to explain the "slope break" in plots of the burning rate of this type of propellant. The aim is to determine the interaction of the propellant ingredients with each other and with binder material. The decomposition products of HMX, TAGN and nitrocellulose (NC) have already been identified in high-temperature reactor studies. Closed-bomb experiments, in atmospheres of the various decomposition products will enable their effect on burning rate to be assessed. Concurrently, time-of-flight mass spectrometry studies will be conducted, first on pure compounds, then on N^{15} isotopically labelled compounds, and finally on blends of labelled and unlabelled species to investigate both mechanism and interaction. Synthesis of TAG $N^{15}{}_{03}$ was accordingly performed.

   The analysis revealed that the nitrate group decomposes at least partially to nitrogen dioxide. In the case of HMX, analysis has provided a plausible explanation of the "slope break" in combustion rate plots. A procedure for the synthesis of N^{15} labelled nitrocellulose (NC), TAGN and HMX has been identified and samples are being prepared.

   2.2. The combustion kinetics of nitramine propellants is being investigated by Fifer and Adams at BRL, ARRADCOM (Ref.4-5). Their object is to study the chemical kinetics of nitrous oxide formaldehyde (N_2O + HCHO) and to compare it with that of nitrogen dioxide formaldehyde (NO_2 + HCHO) in order to determine the relative reactivities of these two nitrogen oxides at "fizz" zone temperatures (600 K – 1500 K) and hence the probable rate-controlling reaction and the flame structure. Preliminary shock tube results indicate that the N_2O + HCHO reaction is considerably slower than the NO_2 + HCHO reaction at "fizz" zone temperatures. A priori estimates of the reaction rates for methoxy and formyl radicals have been obtained by considering weak collision effects for formyl.

   2.3. A study concerning steady-state flame modelling is being carried out by Heimerl at the BRL, ARRADCOM USA (Ref.4-6). The object is to validate the elementary chemical reactions for the HCHO + NO, HCHO + N_2O and HCHO + NO_2 flame systems by making a detailed comparison of their respective theoretical and experimentally measured temperature and chemical species profiles. No indication is given of the state of progress reached with this investigation.

The References 4-13 to 4-17 have been supplied for the work corresponding to paragraph 2.

3. *Reaction kinetics of combustion gases.*

Aulinger and Höh of ISL (FR - Germany) have qualitatively determined the chemical species of the gases sampled along a 20 mm gun barrel in order to describe the reaction kinetics of nitrocellulose propellant gases inside the weapon (Ref.4-18).

Time-of-flight mass spectrographies were carried out in the free jets sampled from two holes in the combustion chamber. The analyses were performed both dynamically on the free jets with the time-of-flight spectrograph and statically on the cooled gases using a quadrupole mass filter.

The analysis of the gases from the barrel revealed no significant difference in the composition of the gases across the two measuring points. On the other hand a marked difference in composition was observed between the gases from the combustion chamber and those from the barrel. The higher CO and CH_4 contents, the appearance of NO and C_2H_4 and the lower H_2, N_2 and CO_2 contents in the chamber would indicate incomplete combustion.

The equilibrium constant for the water gas reaction, determined from these measurements, is reportedly approximately 3 for gases sampled in the barrel and about 4 for those sampled in the combustion chamber.

The presence of the OH-radical in the gases is reported to have been detected. Further, a considerable variation in signal heights for NO and NO_2 could be an indication of erratic burning of the propellant.

4.2.2 Future Work.

1. *Burning rate.*

The investigation into burning rates will be continued at the Research Centre at Le Bouchet up to 600 MPa for an initial propellant temperature of −31, 5°C and + 51°C.

2. *Combustion kinetics.*

2.2.–2.3.

The investigations planned are intended to supplement those already carried out for combustion modelling purposes:

- Full determination of the basic reactions and their respective rates.
- Modelling to enable a large number of elementary chemical reactions.
- Programming and validation of this model in a one-dimensional premixed laminar flame system.
- Computation of temperature and chemical species profiles.
- Investigation of sensitivity of the computed profiles to input parameters.

3. *Reaction kinetics of propellant gases.*

ISL will pursue experimental investigations into the composition of gases along a gun barrel during firings in order to gather sufficient data for statistical evaluation and thereby enable a relation to be established between gas composition and ballistic parameters.

4.3 PHYSICAL CHARACTERISTICS OF PROPELLANT GASES

One-and-two-dimensional interior ballistics models which take account of the boundary layer and gas/barrel and gas/propellant grain heat transfer (ignition) require that certain physical properties of the combustion gases be known, such as specific heat, viscosity and thermal conductivity.

These values are usually known over wide temperature ranges (100 to 5000°K), although, as a rule, for pressures in the region of one atmosphere. It would be of interest to know the values for up to 1000 MPa for the purposes of interior ballistics.

REFERENCES

4-1	Vladimiroff, T.	*Equation of States for Propellant Gases.* Propulsion Branch, Applied Sciences Division LCWSL, ARRADCOM, USA, Private communication, (1979).
4-2	Kuthe, R.	*Preparation of a Programme of Non Equilibrium Reactions.* Dynamit Nobel AG, Köln, Germany, Private communication, (1979).
4-3	Zeller, B.	*Combustion des Poudres.* Société Nationale des Poudres et Explosifs, Centre de Recherches du Bouchet, France, Private communication, (1979).
4-4	Powers, Capt.	*Interaction and Reaction Kinetics of Nitramine Propellants.* Air Force Armament Laboratory, Elgin Air Force Base, Florida, Private communication, (1979).
4-5	Fifer, R.A. Adams, G.P.	*Flame Zone Kinetics.* Propulsion Division, Ballistics Research Laboratory, ARRADCOM, USA, Private communication, 1979.
4-6	Heimerl J.M.	*Steady State Flame Modeling.* Propulsion Division, Ballistic Research Laboratory, ARRADCOM, USA, Private communication, 1979.
4-7	Vladimiroff, T.	*Theoretical and Empirical Equations of State for Nitrogen Gas at High Pressure and Temperature.* In press.
4-8	Grune, D. Kegler, W.	Abbranduntersuchungen von Treibstoffen bei hohen Drüken .2. Teil: Überprüfung der Abelschen Zustandsgleichung verschiedener, Treibstoffe im Druckbereich von 3 bis 7 kbar, ISL, Report RT 518/77.
4-9	Behrens, H.	Virialgleichung und Kovolumen von Pulvergasen, ISL, Report R 117/78.
4-10	Grune, D.	*Innenballistische Leistungsstreigerung von Rohrwaffen.* Auswertung von Bombenversuchen bei hohen Drücken. Proceedings Symposium, ICT Berghausen, 29.11., 1.12. 1978 or ISL, Report 204/79.
4-11	Volk, F. Bathelt, H.	*Application of the Virial Equation of State in Calculating Interior Ballistics Quantities.* Propellants and Explosives 1 (1976) 7-14.
4-12	Volk, F. Hund, M.	*Leistungsdaten von Triebmitteln: Ein Vergleich zwischen Theorie und Praxis.* Proceedings of the 3th International Symposium on Ballistics 23-25 March 1977 in Karlsruhe, FRG.
4-13	Adams, G.F.	*A Priori Estimation of Rate Constants for Unimolecular Decomposition Reactions.* ARRADCOM-TR in press.
4-14	Fifer, R.A.	*Shock Tube Study of the High Temperature Kinetics and Mechanisms of Nitrogen Dioxide-Aldehyde Reactions.* Proc. 10th Intern. Shock Tube Symposium, Kyoto Japan, July 1975, Published in *Modern Developments in Shock Tube Research,* G.Kamimoto, ed, Shock Tube Research Society of Japan, 1975, pp. 613-620.
4-15	–	*High Temperature Pyrolysis of Methyl (and Ethyl) Nitrate,* 17th Symposium (International) on Combustion, Leeds, UK, August 1978, The Combustion Institute, 1979, in press.
4-16	Heimerl, J.M. Coffee, T.P.	*The Unimolecular Ozone Decomposition Reaction,* Combustion and Flame 35: 117-123 (1979).
4-17	Coffee, T.P. Heimerl, J.M.	*A Method for Computing the Flame Speed for Laminar Premixed One-Dimensional Flame,* Technical Report AR BRL-TR-022 12 - January 1980.
4-18	Aulinger, F. Höh, A.	Versuche zur massenspektrometrischen Analyse der Pulvergasschwaden beim Schuss ISL-Report CO 201/79.
4-19	Nicolas	*Study of the Behaviour of Propellants-Combustion Products at High Pressure.* (SNPE). (International Symposium of Gun Propellants - Oct. 73 - Picatiny Arsenal).

Chapter 5

SPECIFIC PROBLEMS IN INTERIOR BALLISTICS

5.1 LIQUID PROPELLANT FLOW

5.1.1 Introduction

One of the major advantages of liquid propellants is the potential for high loading densities (1g/cm^3) with the concurrent very high energy densities. The energy content of liquid propellants which have been considered for gun applications range from 2,5 Mj/kg to 1,35 Mj/kg and more (Ref.5-4). The search for liquid propellants with low vapor pressure, low toxity and safe handling properties under ambient conditions resulted in propellants which are difficult to initiate into sustained combustion under ambient pressures. There are two types of liquid propellants for gun applications

- mono-propellants
- hypergolic bipropellants.

The mono-propellants can be bulk loaded in the combustion chamber and then initiated, or can be injected during combustion, necessitating an ignition system. The hypergolic bipropellants are simultaneously injected in the combustion chamber and continue to be injected during combustion, necessitating injection pressures much higher than those in the combustion chamber.

5.1.2 Experimental work

Many studies are performed in the USA on controlling ignition and combustion of the monopropellant in the chamber, since reproduction of the ballistic performance is still a major problem. Different phases in the bulk loaded liquid propellant gun (BLPG) can be distinguished (Ref.5-3, Ref.5-5):

- propagation of a pressure wave in the propellant due to functioning of the ignition system
- formation of a gas bubble emanating from the ignition system
- instability of Taylor in the accelerated propellant
- Helmholtz mixing at the interface combustion gas propellant, due to their different speeds.

In the Propulsion Technology Branch, ASD, Large Caliber Weapons Systems Laboratory, ARRADCOM USA, the sensitivity to initiation by explosive-generated shocks (card gap tests) has been determined for a liquid monopropellant (NOS 365) as a function of bubble content and temperature (Ref.5-2). The bubble profiles have been photographed in a transparent gun. Together with Princeton Combustion Research Laboratory, the mechanism of ignition by collapse of vapor bubble has been investigated, by construction of an apparatus for applying rapid compression to small specimens. In Ref.5-4, some unique ignition and combustion aspects of liquid propellants have been described. In a closed chamber of 50 cm^3, with optical windows, survey tests on ignition, decomposition and combustion have been performed on 4 different mono-propellants over various pressure ranges up to about 100 MPa. The monopropellant was ignited by an electrically heated wire. The transmitted light from the back light, and/or the emitted light from combustion process was recorded on color film and also by a more sensitive photo diode detector. The diode signals were recorded on the same magnetic tape as the pressure and provided a convenient means of correlating the rate of change in luminosity with pressure. In a normal ignition-combustion sequence, different phases can be distinguished:

- ignition
- exothermic (fizz) decomposition without a flame
- transition to combustion with flame.

It has been observed that some “safe” monopropellants appeared to be unable to support combustion with flame under ambient condition thereby releasing only a minor part of the available energy. In practically all cases, some pre-pressurization of about 3,5 MPa was necessary in order to obtain a normal transition into the flame mode. Data have been collected which indicate that the ignition of hydro-alumoniumnitrate (HAN) type monopropellants is strongly dependent upon the pressure and definitely will not support flame combustion below some threshold pressure or density of its early decomposition (fizz) products. Data were also included on how the ignition and transition (threshold) pressure depends on variations in the initial pre-pressurization, the oxidizer (fuel ratio, the total concentration of propellant and the amount of gelling agent). Because of the very hard to-ignite and low energy fizz (flameless) combustion of the HAN liquid monopropellants at pressure orders of magnitude above atmospheric, they offer a potential for low vulnerability and excellent safety and handling characteristics. At the same time, however, these same characteristics offered some inconvenience: ignition delays, hang fires, overpressures and extremely low pressure and low velocities in some gun firings.

5.1.3 Modeling

At the Interior Ballistics Division, BRL, ARRADCOM, USA (Ref.5-1), a 2D fluid dynamic code for the simulation of the bulk-loaded liquid propellant gun (BLPG) has been initiated. Initial development has been completed and several test calculations have been made. The code has been used to simulate a Lagrange gun and results compare well with the analytical solution of Love and Pidduck. A simulation of a BLPG firing has also been made and the results compared to experimental data and to a similar calculation done at Los Alamos Scientific Laboratory. It has been found that both the development of the flow field and the ballistics are strongly dependent on the turbulence model used in the simulation. Work on regenerative liquid propellant gun (RLPG) models has been carried out by the General Electric Company. These are lumped parameter models which are dependent on empirical correlations as inputs to the combustion model. However, given combustion chamber conditions, system response is accurately predicted. Therefore, these models are useful tools in the analysis of firing data. The compression ignition problem is being studied both experimentally and theoretically. A model of the oscillation of a single bubble in an incompressible liquid has been developed at the BRL. The response of the bubble to a rapidly rising pressure in the liquid has been determined. Prepressurization has been found to significantly affect bubble response. Combustion of the propellant at the gas liquid interface has also been investigated.

Future work will include:

- continuation of the development of the BLPG code and the refinement of physical submodels.
- an attempt to improve the combustion model in RLPG simulations.
- inclusion of liquid compressibility and heat transfer in the compression ignition simulation.

The importance of condensed phase compressibility to bubble behavior has been shown in theoretical studies (Ref.5-5) and (Ref.5-6). Interior ballistics modeling for liquid propellant guns is also being pursued in France by the Direction des Recherches, Etudes et Techniques (DRET), with investigations being carried out by SNPE-CRB. The objective of their work is to prepare an interior ballistics model for guns which use hypergolic bipropellants in order to carry out parametric studies at the lowest possible costs. A 1D-calculation technique based on a simple physical model relating to the laws of combustion and droplet formation has been devised. The numerical method used, combines the method of finite differences for points in the interior with the method of characteristics at the breech and of the base of the projectile. This method has been prepared assuming the separation of the phenomena of propellant injection and combustion, though future plans include coupling of these processes.

REFERENCES

5-1	Watermeier, L.A.	Propulsion Division, BRL, Private Communication, March 1979.
5-2	Watermeier, L.A.	Propulsion Division, BRL, Private Communication, March 1979.
5-3	Zeller.	SNPE, Centre de Recherches du Bouchet, Private Communication, January 1980.
5-4	Comer, Dr Travis, Dr	Interior Ballistics Division, BRL, *A Review of Some Unique Ignition and Combustion Aspects of Liquid Propellants.*
5-5	Comer, Dr	Interior Ballistics Division, BRL, *Fluid Dynamic Aspects of Bulk-Loaded Liquid Propellant Guns*, AGARD Conference Proceedings No.10.
5-6	Reuven, B. Summerfield, M.	Princeton Combustion Research Laboratory (PCRL), Princeton, New Jersey, *Theory of Bubble Dynamics in Condensed Explosives During Start-Up Transients*, (to be published in AIAA Journal).

5.2 EROSION (ADDITIVES FOR EROSION)

5.2.1 Introduction

The first part "Study of the erosion mechanism", treats the basic mechanisms of erosion. The fluid dynamic aspects of erosion have been treated mainly in the fundamental work of Buckingham. The other aspects are only mentioned somewhere through the text, but for further details on this point, the reader is urged to consult the publications from other NATO Working Groups. The second part deals with "Control and measurement of erosion". Control of erosion is here limited to the use of additives and ablatives in order to reduce the bore surface temperature. A thermal and erosion sensing technique, developed by the Calspan Corporation, requiring only a few shots in order to determine the thermal and erosion wear characteristics of an individual tube ammunition combination, constituted certainly a marked progress in measurement technique.

5.2.2 Study of the Erosion Mechanism

(a) Basic Mechanisms

Some work on erosion characterization has been performed and is still ongoing by A.Niiler – BRL (Ref.5-7). Attempts were made to obtain details of the erosion mechanism from the surface characterization of eroded steel. A correlation between oxygen and nitrogen steel surface concentrations and the temperatures could be established from tests in which the combustion products from burning propellants with different flame temperatures were passed across a steel nozzle. These results support evidence for the two distinctly, well-known, erosion mechanisms (i) melt and wipe-off and (ii) formation of an altered layer whereby the surface temperature is the governing factor in this process. Additional experiments with nitrogen implanted nozzles have been carried out. These nitrogen implanted nozzles seemed to show a slight improvement in erosion resistance during the first few shots. Further tests with steel nozzles, ion plated with chrome by Dr Tear at the University of Salford, will be conducted in the future. Some work has been done on "Barrel erosion of gunpowder" and "Consideration about Barrel-life-time" by resp. Dr Vasatko, Mangel and Dr Vasatko of WNC – Nitrochemie GmbH (Ref.5-8). The second part of the contribution deals with mechanisms of gun barrel wear life and erosion by different propellant compositions. The wear and erosion in a weapon can be simulated in a special laboratory gun simulator which operates with special removable metal inserts.

(b) Fundamental Work of A.C.Buckingham (Lawrence Livermore Laboratory)

The fluid dynamic aspects have principally been treated by Buckingham (Ref.5-13 to Ref.5-16). The author presents some models that describe the fundamental mechanisms of erosion, based on fluid dynamics combined with Monte Carlo techniques of randomization. The dominant flow features taken into consideration by the author are:

- turbulent combustion propellant core
- circulation in the forcing cone at the original point of separation between propellant charge and projectile
- a growing turbulent wall boundary layer and attenuating turbulent core behind the projectile.
- projectile-to-wall contact interface.

The main part of the studies treats the mixing and interaction between the turbulent propellant core and the developing wall boundary layer, and the radial non-uniformity of the flow. The fluid dynamic situation which develops, includes the solid aerosol consisting of sparse distributions of unburned propellants and erosion suppressive additives such as finely divided TiO_2, SiO_2 and talcum powder. The author then proposes models in order to describe the turbulent core flow, particulate coupling and boundary layer. Due to the sparse distribution of particulates in turbulent core flow, it is assumed that the turbulent gas flow field and thermal field is unaffected by the particles. Buckingham obtains the sparse particle distribution using a Monte-Carlo randomization of the turbulent velocity about the mean gas velocity, over incremental time steps. The primary erosion reducing influence of particulate additives, when small enough to disperse rapidly and produce significant population concentration at the walls, appears to be in:

- mass-inertial and displacement effects which reduce the gradients driving the erosive heat transfer at the wall
- particle flow in the boundary layer which forms a motile near-surface layer acting to scatter incident particulates and fragments preventing them reaching the wall
- near wall flow of small size particles offers a considerably greater surface area than does the exposed wall: hence it is an effective chemical absorption layer for exothermic chemical reactions
- particulates in the core flow may provide significant acoustical damping of the high frequency pressure oscillations and lower the intensity of the combustion originated turbulence.

Nevertheless, the author underlines the fact that the fundamental questions on the basic mechanisms by which additives suppress erosion, still remain. Dr Buckingham compared measurements of the in-bore radial temperature and velocity in a small cannon (20 mm) during firing experiments of Klingenberg and Mach at the Ernst Mach Institute, with the predicted radial gradients.

5.2.3 Control and Measurement of Erosion

The most important ways to control erosion, are:

- reduction of the bore surface temperature, mainly through the use of dimethylsilicone based ablatives and metal oxide/wax liners added to a propellant charge
- use of low flame temperature propellants
- reduction of the engraving pressures on the bore surface and band material bore surface interaction.
- coating gun barrels with erosion resistant materials.

The following contributions deal with the use of additives and ablatives in order to reduce the bore surface temperature. First, some work performed (and still ongoing) by A.Niiler from BRL on "Erosion Process Characterizated" was mentioned in Ref.5-9. The objectives of the study of additives for erosion in large caliber weapon systems were to assess the optimum type, quantity configuration of a wear reducing additive. The relative erositivity reduction for given wear additive types, quantity configuration is evaluated in an actual gun using thermal and erosion sensor by firing a small number of rounds (5–15) in a given series (tests were performed jointly with the Calspan Corporation). The tests were performed with the use of silicone ablators, TiO_2/wax and talc/wax as additives, and super-slurper materials (super-slurper is made from a small amount of diaper material and is mostly glycol/water: they are able to absorb up to 900 times their weight in glycols and water). Evaluation of the results showed, for a given weapon-ammunition system, that the best performance against erosion was obtained with the silicone ablator, which reduced greatly the heat input to the barrel and showed no erosion on the erosion sensor. The super-slurper gave similar heat input to the standard round, but no erosion was observed on the erosion sensor after 5 shots. Future tests of this material, impregnated with TiO_2, talc and silica are planned. New additive screening is performed in a laboratory erosion simulator prior to gun testing. Wear optimization studies are performed on all new high performance rounds. Secondly, some work, still on-going, by Zimmermann, from ISL on "Wear reducing additives for gun tubes" has been mentioned by Ref.5-10. This contribution investigated the mode of action of wear reducing additives in gun tubes of 20 mm and 30 mm in caliber. The investigated additives were wax, wax/talc and wax/TiO_2 used as liners as well as talc and TiO_2 used as powder additives in different proportions. The effects of the investigated additives, used in the form of liners, are almost the same. Used as powder additives, talc causes the wall temperature to decrease. Because of the particular flow feature near the base of the projectile, the author will study the effects of additives transported from the projectile to the wall of the tube or into the boundary layer during projectile movement in the tube. It seems possible to obtain initial information on erosion of different propellants from comparative measurements in the erosion simulator (Ref.5-8). The erosion effect in weapon can be simulated in a special gun with removable metal inserts. A thermal and erosion sensing technique has been developed by the Calspan Corporation, requiring only a few shots in order to determine the thermal and erosion wear characteristics of an individual tube-ammunition combination (Refs 5-9, 5-11, 5-12). Although it is not a method for establishing the absolute value of gun life, it is an excellent method for rating the potential of candidate designs against a known performer (Ref.5-11). The thermocouple installation used for determination of the temperature at the contact point (which enables the calculation of the heat input per unit area at the bore surface), is formed by stainless-steel-sheathed gage, chromel-alumel thermocouple wires which are forced into contact with the flat-bottom hole by the action of a compressed spring. A small amount of silicone grease is placed into the hole prior to insertion of the thermocouple to fill void spaces and decreases the small thermal resistance introduced by the presence of the hole. The erosion sensor, comprises two chief components: a sensor holder and a sensor. Accurate placement of the erosion sensors, required the fabrication of special removable erosion sensor holders (made from chrommoly vanadium steel). A diamond indenter of the "Knoop" type was employed to place several indentations on all sensors surfaces (Ref.5-12). This indenter produced a sharp impression with a constant ratio of length to depth of 30 : 1. The impressions serve as a gage by which erosion or wear may be measured after firing. After forming the surface impressions, the surface of each sensor was characterizated prior to test by photomicrographes (SEM) at 275 x magnification. Post test examination of the erosion sensors indicates the amount of erosion. Correlation of heat input and erosion measurements in most cases (Ref.5-11) can be obtained.

5.2.4 References to Recent Published Reports of Activity (Open Distribution)

See Reference 5-18 to Reference 5-23.

REFERENCES

5-7	Watermeir, L.A.	Chief Propulsion Division, BRL, Private Communication, March 1979.
5-8	Krauth, G.	Dipl. Phys., ISL, Private Communication, April 1979.
5-9	Watermeir, L.A.	Chief Propulsion Division, BRL, Private Communication, March 1979.
5-10	Krauth, G.	Dipl. Phys., ISL, Private Communication, April 1979.
5-11	Lader. R.W. Russell Wurzel	Propulsion Technology Branch, Applied Sciences Division, Large Caliber Weapon System Laboratory, ARRADCOM, Dover, N.J. *Optimization of Wear Reducing Additive for 105 mm Cartridge, Heat M 456.*
5-12	Downs, D.S. Lannon et al.	Large Caliber Weapon Systems Laboratory, USA ARRADCOM, Dover, N.J. Calspan Corporation, Buffalo, N.Y. *Wear Additive Optimization Studies for the High Zone Charge in the 155 mm Artillery System.*
5-13	Buckingham, A.C.	University of California, Lawrence Livermore Lab., *Propellant Driven Turbulent Interior Ballistics and Wall Erosion*, 17th Aerospace Sciences Meeting, New Orleans, January 15–17, 1979.
5-14	Buckingham, A.C.	Lawrence Livermore Laboratory, *Modeling Additive and Hostile Particulate Influences in Gun Combustion Turbulent Erosion*. Proceedings of the 1979 CPIA-IANNAF Combustion Conference, U.S. Naval Postgraduate School, Monterey, California, September 10–14, 1979.
5-15	Buckingham, A.C.	Lawrence Livermore Laboratory, *Dusty Gas Influences on Transport in Turbulent Erosive Propellant Flow*. AIAA 18th Aerospace Sciences Meeting, Pasadena, California, January 14–16, 1980.

5-16 Buckingham, A.C. — Lawrence Livermore Laboratory, *Modeling Propellant Combustion Interacting with an Eroding Solid Surface*. AIAA-SAE-ASME, 16th Joint Propulsion Conference, Hartford, Connecticut, Jun 30–July 2, 1980.

5-17 Klingenberg, G.; Mach, H. — Ernst Mach Institute, *In-Bore Measurements of Gas Velocity and of Radial Gas Temperature Distributions*, in Proc. 4th International Symposium on Ballistics, sponsor, American Defense Preparedness Association (U.S. Naval Postgraduate School, Monterey, Cal., November 1978).

5-18 Vassallo, F.A. — *Evaluation of Heat Transfer and Erosion in the 155 mm M185 Cannon*, Calspan Technical Report No. VL-5337-D-7, July 1976.

5-19 Vassallo, F.A. — *Heat Transfer and Erosion in the ARES 75 mm High Velocity Cannon*, Calspan Technical Report No. VL-5645-D-1, October 1975.

5-20 Niiler, A.; Youngblood, J.E.; Caldwell, S.E.; Rock, T.J. — *An Accelerator Technique for the Study of Ballistic Surfaces*, BRL Report No. 1815, August 1975.

5-21 Geene, R.W.; Ward, J.R. et al. — *Erosivity of a Nitramine Propellant*, BRL Technical Report AR BRL-TR-02094, August 1978.

5-22 Brosseau, T.L.; Ward, J.R. — *Measurement of Heat Input into the 105 mm M68 Tank Cannon Firing Rounds Equipped with Wear Reducing Additives*, Technical Report AR-BRL-TR-02056, April 1978.

5-23 Picard, J-P.; Ahmad, I. — Proceedings of Tri-Service Gun Tube Wear and Erosion Symposium, 29–31 March 1977, sponsored by American Defense Preparedness Association at U.S. Army Armament Research and Development Command, Dover, N.Y.

5.3 COMBUSTION AND MECHANICAL PROPERTIES OF SOLID PROPELLANTS AT HIGH PRESSURE

5.3.1 Introduction

The objective of this Section is to propose a brief summary of the state of the art on combustion and mechanical properties of solid propellants at high pressures. Since the actual trend in modern weapons, especially in tank cannons is to increase the muzzle velocity, high loading densities and high pressures are encountered in fire arms, with the following problems: mechanical response of the packed bed and combustion at high pressure. These two subjects will be treated in the next paragraphs.

5.3.2 Mechanical Behaviour of the Propellant at High Pressure

In order to explain some "abnormal" pressure peaks observed in gun firings, some authors assume a break-up of propellant grains, others believe that the phenomenon is caused by uncontrolled pressure waves due to unsatisfactory ignition (especially in high loading density charges). This seems applicable for granular type propellants which, for comparison, stick propellants for small loading density, experiences much less stress over its length and, consequently the "break-up" phenomenon is far less evident. Investigation on propellant break-up, has been undertaken at Arradcom (Ref.5-25) and SNPE (Ref.5-26). The action of the propellant grains, when accelerating toward the base of the projectile and the tube wall, has been simulated by throwing propellant grains against a steel plate by means of a launching device (Ref.5-26) or by compression (Ref.5-25). In Ref.5-25, several triple base gun propellants and one modified double based propellant now in field use and one nitramine gun propellant formulation, have been studied in compression. The results indicate that the type of failure (break-up), stress and strain at failure and the toughness strongly depend on temperature and loading rate. At low temperatures and high loading rate, a very brittle fragmentation is observed while at low loading rates, a much more ductile type of failure is observed. The type of failure is dependent on the type of loading and the web size of the sample. As the mechanical properties of the propellants investigated, are largely determined by the polymer and plasticizer content and properties, it should be possible to draw on the extensive literature on mechanical properties of polymer/plasticizer systems to tailor propellant compositions to give the desired mechanical properties. In the future, propellant grains and formulations will be subjected to more severe and complex loading conditions in order to approximate the ballistic environment conditions. The mechanism of failure will be investigated with a scanning electron microscope and through studies of molecular bound breaking by electron spin resonance. In (Ref.5-26), tests have been performed on multi-perforated propellant grains with various geometries and compositions.

- one 19 holes single base propellant without plasticizer
- one 19 holes single base propellant with dinitrotoluene and dibutylphtalate
- one 7 holes single base propellant without plasticizer
- one 7 holes triple base propellant.

Samples of each category, kept for 6 hours at desired temperatures (−54°C, 21°C and 51°C), have been launched against a steel plate. By regulating the pressure in the launching device, it was possible to evaluate the impact at different velocities up to 250 ms^{-1}. The test procedure permits to plot the percentage of broken grains versus impact velocity. The influence of temperature, geometry, composition and even the manufacturing process of the propellant grains on their mechanical behaviour, could be established. It has been stated that

- propellants are more brittle at low temperatures and therefore the percentage of broken grains was the highest at the lowest temperatures
- at low impact velocities, a 7 holes grain seems to be more resistant than a 19 holes grain, but at high impact velocities, the 19 holes seems to be more resistant
- it seems possible to improve impact resistance of propellant grains, solely by adjusting the manufacturing process.

The break-up modes were also investigated, varying from a simple break-up in 2 fragments, to some kind of dust, especially at high impact velocities. The influence of the broken grains on the ballistic performance is determined next. Thereto the fragments of broken grains are put together in a high pressure closed bomb, in order to assess the importance of charges in apparent burning rate.

5.3.3 Combustion at High Pressure

Quite recently, the strand burner, formerly used to determine the burning rate for rocket propellants, was also used for the determination of the burning rate of solid propellants at conventional gas pressures in arms. At ISL and SNPE, comparative tests in strand-burners and high pressure bombs have been undertaken (Ref.5-24, Ref.5-27). The volume of the combustion chamber of the strand-burners was 700 cm^3 and it resists up to 700 MPa. A direct measurement of the burning rate is done, by measuring the time of combustion of samples. In order to obtain a linear and longitudinal combustion, the propellant was inhibited. The test is performed at a series of constant pressures by regulating the pressure of nitrogen gas, that was introduced into the bomb. In order to withstand pressures in a range of 300 to 700 MPa a new high pressure bomb of 92,7 cm^3 was built; a high pressure BROSA gauge, type ISL, was also used. A blowoff nozzle serves to unload the bomb after test: it opens automatically, 30 to 50 ms after the maximum pressure had been reached. Various tests on single-base, double-base, double-base composite and nitramine propellants have been performed. The burning rates of a single base propellant, measured with the strand burner were slightly higher than those obtained from high pressure bomb data. The maximum gas pressures of these conventional propellants, indicate that at about 500 MPa and more, the force constant as well as the covolume in Abel's equation are no longer constant. The starting point of the discrepancy apparently depends on the kind of the propellant and seems to be opposite to the oxygen balance. The deviations from Abel's equation are explained by the virial coefficients of the combustion products. Investigation of heterogeneous nitramine propellants (Ref.5-24), showed that the virial equation remains applicable, but that the usual calculation of the burning rate did no longer hold (the vivacity curves do not correspond to the geometry of the propellant elements).

5.3.4 Future Work

In the future, it will be tried to determine more exactly the conditions (temperature, composition, type of loading) under which mechanical failure may lead to abnormal gas generation rate and so to abnormal ballistic performance and even breech blows. Obtaining highly accurate measurements in bomb firings, seems to be one of the major problems. Finally the goals of the studies are, besides the acknowledgement of the real phenomena, to modify formulations in order to prevent mechanical failure that can lead to abnormal ballistic performance, to develop standard tests and specifications for the mechanical properties of solid propellants.

5.3.5 References to Recent Publications

See Ref.5-28 to Ref.5-34.

REFERENCES

5-24	Krauth, G.	Dipl. Phys., ISL, Private Communication, April 1979.
5-25	Watermeier, L.A.	Chief of Propulsion Division, BRL, Private Communication, March 1979.
5-26	Benhaim, P. Paulin, J.L. Zeller, B.	SNPE, *Investigation on Gun Propellants Break-up and its Effects in Interior Ballistics.*

5-27	Grune, D. Kegler, W. Nicolas, M. Benhaim, P.	From ISL and SNPE, *Studies of the Combustion of Solid Propellants at High Pressures.*
5-28	Wiegand, D.A.	*Mechanical Properties of Propellants*, Large Caliber Weapon Systems Labcratory, Review of Research and Exploratory Development in Energetic Materials, October 1978.
5-29	Wiegand, D.A.	*Mechanical Properties of Propellants*, Review of Arradcom Program in Large Caliber Gun Propulsion Technology, (Poster Session), November 1978.
5-30	Kegler, W. Grune, D. Daniels, W. Carrière, A.	*Abbranduntersuchungen von Treibstoffen bei hohen Drücken. 1 Teil: Konstuktion und Erprobung einer Hochdruckbombe*, erste Ergebnisse-Rechenprogramm für die Datenverarbeitung, ISL-Report RT 521/76.
5-31	Grune, D.	ISL, *Studies of the Combustion of Solid Propellants at High Pressures Propellants and Explosives 2/76 S.27.*
5-32	Grune, D. Kegler, W.	ISL, *Abbranduntersuchungen von Treibstoffen bei hohen Drücken. 2 Teil: Uberprüfung der Abelschen.* Zustandsgleichung verschiedener Treibstoffe im Druckbereich von 3 bis 7 Kbar, ISL-Report RT 518/77.
5-33	Kegler, W. Grune, D. Nicolas, M. Benhaim, P.	From ISL, *Studies of the Combustion of Solid Propellants at High Pressures*, Proceedings of the 3rd International Symposium on Ballistics. A:2. or ISL-Report CO 209/77.
5-34	Grune, D.	ISL, *Durchfüring von Abbranduntersuchungen mit der 100* cm^3 *– Hochdruckbombe* – ISL-Report N611/77.

Chapter 6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

This report comprises five Chapters:

(a) The first reports briefly the goal of the work and the manner in which it has been carried out.

The initial aim consisted of examining the extent to which recent progress achieved in Fluid Dynamics could further contribute to internal ballistics developments, in particular in the area of modelling.

In fact it became rapidly clear that specialists in interior ballistics were sufficiently aware of fluid dynamics progress to include them in so far as they needed to.

Therefore we have aimed more at presenting a review of the present state of the art and at underlining flow areas or mechanisms in which knowledge seems to be still uncertain or lacking in precision.

(b) The second Chapter can be considered as the main part of the report.

First, the numerical methods presently in use or in development, describing the gun firing: their goal, their base, and their development state are presented. Messrs Horst, Watermeier, East and Schenk clearly underline the effort being made to ensure the coupling between the initial, complex, but determining ignition and burning phase, with the subsequent flow in the tube. He presents then the methods being used to attempt the description of the hot, reactive, multiphase, instationary boundary layer on the tube.

Finally, this Chapter is illustrated by the presentation of the results of a calculation exercise performed on the same interior ballistic problem using four different numerical codes, three of them being currently used for loading studies, the fourth one being only in a development phase.

Thereafter, the experimental methods and theories are dealt with which support numerical codes, furnish the necessary empirical data and allow for their experimental control. Dr Baiocchi first describes the complicated ignition and burning process which intimately mixes gas dynamic phenomena (hot gaseous flow, waves phenomena) with chemical reaction and mechanical processes of compaction and rupture of powder grains. The analysis of this early phase of the interior ballistic process is the purpose of very active research done, from a theoretical point of view in order to get insight into each elementary phenomenon as well as from the point of view of the experimental technique to be used. MM Krauth and Heyser report then on the biphasic, gaseous flow in the tube after the projectile has started. A minute check is made of the state of development of the experimental techniques used to measure the main parameters describing this flow. One may observe that the methods are either becoming satisfactory or attempt to accommodate modern metrology to this specific goal (Laser velocimetry, X Ray cinematography). Nevertheless, no suitable method is available to allow investigation of boundary layers, to measure heat transfer, or to analyse flow near projectile base and gas leakage.

(c) The third Chapter, by Dr Pagan, is devoted to gas outflow and related problems (intermediate ballistics of the projectile, sabot discard). The reader will see that, despite the complexity of the outflow and the associated wave phenomena, the existing numerical codes seem to furnish a description of both the flow and associated blast phenomena, which is sufficient for practical use, provided that physical quantities in the exit plane of the tube (or of the nozzle) are sufficiently well-known.

(d) The fourth Chapter, by M.Soulage, reports on the state of knowledge concerning the physicochemistry of combustion gases: State equation, combustion rate, reaction kinetics, physical properties of combustion gases. It can be said that, if the two first items are the subject of a very active research for a very long time, reliable information is completely missing with respect to the third item which appears, however, essential as far as boundary layer and heat transfer are concerned.

(e) The last Chapter is devoted to the presentation by Cdt de Cock of a few particular problems of internal ballistics such as liquid propellants, tube erosion, combustion and mechanical properties of solid propellants at high pressure. Among the numerous problems encountered in the field of liquid propellants (in particular, research with products of optimal physical and chemical properties), the importance of the fluid dynamics problem of injection of propellant and of the phenomena which follow immediately the ignition phase must be underlined.

The description of the erosion mechanism and of the presumed action of anti-erosion additives shows once more the essential role played by the boundary layer along the tube and by the flow in the vicinity of the projectile base.

6.2 CONCLUSIONS

1. The examination by the Working Group of Fluid Dynamics Aspects of Interior Ballistics underlines the close linkage between fluid mechanics progress and the present development of numerical codes in interior ballistics. Likewise, in the experimental area, the same goal exists which aims at adapting to the more severe condition of interior ballistics, techniques initially developed for study of aerodynamic phenomena (Laser velocimetry for instance). Some basic mechanisms of internal ballistics, however, still remain quantitatively incompletely described. This is especially true for the case of erosion processes. But the present effort of understanding developed on both sides of the Atlantic (development of bi-dimensional codes furnishing a more and more precise description of boundary layers and flow in the vicinity of the projectile, fundamental studies of heat transfer in the boundary layer and at the interface between boundary layer and tube, basic experiments made with simulators using clean gases acting on a piston) promise fast progress on such subjects.

2. The members of the Working Group appreciate the importance, quality and complementary nature of the work done in the various countries concerned. Exchanges of information were judged very fruitful and the wish has been expressed to see maintained, after the Working Group has achieved its task, the cooperative work that it has initiated. It is therefore suggested that the possibility of setting up such a group under the auspices of an adequate authority of NATO should be examined.

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14.Abstract

Increased computer power, new numerical methods, and modern test facilities have led to improved modeling of turbulent events, and particularly in the methods available for analysing and predicting fluid flows in interior ballistics. Six NATO countries contributed to a Working Group charged with verifying the extent to which experts in interior ballistics could take advantage of such progress. Experts in fluid dynamics were consulted, as were authors of various computer codes who provided insight into their objectives and code contents. Chapters deal with the interior ballistics cycle, gaseous outflow from tube launchers, characteristics of propellant gases and specific problems in interior ballistics.

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