UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

AD-A193 598

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S): ARO 20007.10-EG

6a. NAME OF PERFORMING ORGANIZATION: The Pennsylvania State University

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION: U. S. Army Research Office

6c. ADDRESS (City, State, and ZIP Code): University Park, PA 16802

7b. ADDRESS (City, State, and ZIP Code): P. O. Box 12211, Research Triangle Park, NC 27709-2211

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: U. S. Army Research Office

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: DAAG29-83-K-0081

8c. ADDRESS (City, State, and ZIP Code): P. O. Box 12211, Research Triangle Park, NC 27709-2211

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification): "A Study of Flame Spreading and Combustion Phenomena of Stick Propellants"

12. PERSONAL AUTHOR(S): K. K. Kuo and W. H. Hsieh

13a. TYPE OF REPORT: Final Report

13b. TIME COVERED: FROM 5/83 TO 12/87

14. DATE OF REPORT (Year, Month, Day): 1988, February 29

15. PAGE COUNT: 15

16. SUPPLEMENTARY NOTATION: The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Combustion, flame spreading, grain rupture, erosive burning, strand burning, real-time X-ray radiography, digital image processing technique, stick propellants, NOSOL-363, two-phase combustion model

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Please see reverse.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

The flame spreading and combustion phenomena of stick propellants were studied both experimentally and theoretically in three major research areas: (a) investigation of the flame-spreading and combustion processes inside a single stick propellant under controlled external pressurization; (b) study of the strand- and erosive-burning characteristics of stick propellants; and (c) investigation of combustion phenomena of stick propellant bundles under simulated gun conditions. A comprehensive theoretical model for each of the research areas was formulated, solved numerically, and validated by experimental data. Experimentally, four combustion chambers were designed to conduct single-stick, erosive-burning, strand-burner, and stick-bundle tests. It was found that the critical pressure differential for stick propellant grain rupture increased monotonically with pressurization rate, and the critical pressure differential can be substantially higher at rapid pressurization rates than at steady-state conditions. From research area (b), the real-time X-ray radiography technique proved to be a nonintrusive, powerful and reliable tool for determining erosive-burning rates under confinement conditions. The combustion wave structures under erosive- and strand-burning conditions of NOSOL-363 stick propellants were measured by fine-wire thermocouples. From research area (c), the pressure-wave phenomenon with combustion of the stick-propellant charge was found to be less than that of conventional multi-perforated granular propellant beds. The two-phase combustion model developed on this project has been shown to predict many important combustion characteristics of stick propellant bundles.

ARO 20007.10-EG

A STUDY OF FLAME SPREADING AND COMBUSTION PHENOMENA OF STICK PROPELLANTS

FINAL REPORT

Submitted to

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Engineering Sciences Division

U.S. Army Research Office

Research Triangle Park, NC 27709

Contract No. DAAG29-83-K-0081

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February 1988

Statement of the Problem Studied

Single-perforated long stick propellants offer many advantages over conventional multi-perforated granular propellants in large caliber gun systems. There is a lack of basic understanding of the potential mechanisms of flame-spreading and combustion of stick propellants.

In order to achieve an indepth understanding of the intricate phenomena associated with stick propellant combustion, this program has been divided into three major task areas: (a) investigation of the flame-spreading and combustion processes inside a single stick propellant under controlled external pressurization; (b) study of the erosive burning characteristics of stick propellants under cross-flow conditions; and (c) investigation of combustion phenomena of stick propellant bundles under simulated gun conditions.

Summary of the Most Important Results

In task (a), the research program was undertaken to investigate the flame spreading, combustion, grain deformation, and rupture of single-perforated unslotted stick propellants. Both theoretical and experimental methods were employed to study this complicated and coupled combustion/structural problem.

In the theoretical analysis, a comprehensive theoretical model for predicting the flame spreading, combustion, grain deformation, and rupture process has been developed. Three regions are considered in the analysis: 1) internal perforation region; 2) solid propellant region; and 3) external region. A finite-difference scheme is used to solve the flow properties in the gas phase; and a finite-element method is used in the solid-phase analysis.

A windowed test chamber was designed and fabricated to study flame spreading and combustion inside the stick perforation, and mechanical deformation and rupture of the propellant grain under dynamic loading. The test chamber has the capability of measuring both transient pressures inside the perforation at several axial locations and pressures outside the stick propellant. The chamber has two long windows through which the phenomena of flame spreading, combustion, and fracture can be observed. Pressure external to the stick propellant can be kept at a fixed level using compressed nitrogen gas, or filled completely with water. The internal perforation of the stick propellant is pressurized using hot combustion gases generated form a driving motor. The date acquisition system contains a transient waveform recorder to store the pressure-time traces during dynamic pressurization. The time of grain fracture, as well as the critical pressure differential across the propellant web, was determined from the traces and from high-speed movie films. Both high-speed movie and video cameras were used to obtain records of the flame spreading, combustion, and grain fracture.

Some of the major observations and results obtained from task (a) are summarized as follows:

1) The critical pressure differential for grain rupture increases monotonically with pressurization rate; the critical pressure differential can be substantially higher at rapid pressurization rates than at steady operating conditions. Lowering the initial temperature of the propellant grain and increasing the pressurization rate, causes the propellant to behave as a brittle material. Higher critical pressure differential is measured for these test conditions.

2) Recovered test samples show that for low pressurization rates, the grain fractures with one or more longitudinal slits; but at very rapid pressurization rates, the propellant shatters into many pieces. This is important since fragments of the shattered propellant generate a significantly higher total burning surface area, which in turn leads to enhanced burning of the propellant.
3) From SEM photographs, fractured surfaces of shattered propellant pieces show the existence of numerous microcracks. Microcracks are absent in the case of low pressurization rate tests.
4) Ignition is earlier and flame spreading is faster for higher pressurization rate conditions.
5) A theoretical model has been developed to analyze the interaction between combustion processes and grain deformation inside the perforation region of single-perforated stick propellants before propellant rupture. Calculated temperature, pressure, velocity, grain deformation, stress distributions, etc., along the flow direction aid in the physical interpretation of the coupled combustion event and structural mechanics problem.
6) Close agreement was achieved in the comparison of the predicted pressure-time trace with the measured data from test firing.

In task (b), strand- and erosive-burning proceses of NOSOL-363 stick propellants were investigated. A strand burning test chamber was utilized for conducting combustion diagnostics of NOSOL-363 stick propellants. Three modes of combustion processes (fizz burning, unsteady flame, and steady flame) were observed in strand burning tests. Burning-rate exponents were also determined from burning-rate data at various pressures. the thermal wave structure of the propellant was meausred by fine-wire thermocouples. From thermal wave structures, several important thermal and chemical data on NOSOL-363 stick propellants were obtained.

An erosive-burning test rig using a center-perforated cylindrical propellant grain with large web thickness was employed to study the erosive-burning phenomena of NOSOL-363 stick propellants. A unique real-time X-ray radiography system and digital image procesing system was also set up to determine the instantaneous internal burning surface locations and to deduce instantaneous erosive-burning rates of propellant samples.

A comprehensive theoretical model was formulated and solved numerically for simulating erosive-burning processes occurring inside the perforation of a NOSOL-363 stick propellant. Gas-phase and solid-phase regions of the propellant were both considered in the theoretical model. A two-variable joint probability density function was adopted to take into account the interaction of gas-phase turbulence and combustion. A transient one-dimensional heat conduction equation with consideration of subsurface radiation absorption was used to describe the thermal wave structure of the condensed phase of the propellant.

From the study of task (b), several important conclusions have been reached; they are listed below.

1) Real-time x-ray radiography proved to a nonintrusive, powerful and reliable tool for determining erosive-burning rates under confinement conditions.

2) The comprehensive erosive-burning model, based upon quasi-steady and 2-D axisymmetric mean-flow assumption, was validated by experimental data. The calculated time variation of internal diameter distribution along the grain agrees well with measured distributions.
3) The fine-wire thermocouple (5 to 25 μm wire diameters) was incorporated into the erosive- and strand-burning investigations. The thermocouple can be used not only for measuring the temperature variation in the condensed phase, but also for a part of the gas-phase flame structure.
4) Based upon the recorded X-ray images, the instantaneous burning rate of NOSOL-363 stick propellant has been determined under test-motor operating conditions. The erosive burning augmentation factor can be as high as 3.5; this indicates the strong influence of crossflow velocity on propellant burning rate. Therefore, the erosive-burning effect must be properly incorporated to achieve accurate and realistic predictions of stick-propellant combustion performance in gun propulsion systems.
5) From numerical solutions, the erosive burning is found to be the results of enhanced heat feedback from the gas phase to solid propellant resulting from the combined effects of increased turbulent mixing and reduction in flame stand-off distance form the burning surface.
6) Three modes (fizz, unsteady flame, and steady flame) of gas-phase combustion processes were observed in strand-burning tests of NOSOL-363 propellants.

7) Two different sets of burning-rate exponents and coefficients were deduced from burning-rate data obtained from strand-burner tests. The slope break point at P = 2.17 MPa was found to be the boundary of unsteady flame and steady flame modes.

8) From temperature-time traces obtained in strand burning tests, burning surface temperatures were found to be 320°C at 3.4 atm and 520°C at 69 atm.

9) The activation energies for NOSOL-363 stick propellants are 8.13 kcal/mole in fizz and unsteady flame modes, and 14.8 kcal/mole in steady flame mode.

10) From condensed-phase temperature-time trances, the thermal diffusivity, characteristic time constant, and characteristic length of the NOSOL-363 stick propellant are deduced.

The purpose of task (c) is to achieve an indepth understanding of the intricate phenomena associated with stick propellant combustion. In this task, a theoretical and experimental investigation of combustion phenomena of long unslotted stick propellant bundles under simulated gun conditions was conducted. The comprehensive theoretical model formulated is based upon a combined Eulerian-Lagrangian approach to simulate special characteristics of the two-phase combustion processes in a cartridge loaded with a bundle of stick propellants. The model considers five separate regions--internal perforation, solid phase, external interstitial gas phase, and two lumped parameter regions at either end of the stick bundle.

For the external gas-phase region, a set of transient one-dimensional fluid-dynamic equations using the Eulerian approach is obtained; governing equations for the stick propellants are formulated using the Lagrangian approach. The equation of motion of a representative stick is derived by considering the forces acting on the entire propellant stick. The instantaneous temperature and stress fields in the stick propellant are modeled by considering the transient axisymmetric heat-conduction equation and dynamic structural analysis. For the internal perforation region, a set of one-dimensional transient fluid-dynamic equations is formulated by a coordinate system attached to a moving stick. This theoretical model is validated by test data obtained from related experiments performed in other research groups and by experimental studies conducted by PSU.

Major results obtained from task (c) are summarized below.

1) A comprehensive theoretical model for simulating the combustion and rupture phenomena of long, unslotted stick propellant bundles under simulated gun conditions is formulated. Major differences between the present formulation and the conventional interior ballistic predictive models are summarized in Table 1.

2) An efficient computer code has been developed to solve the theoretical model describing flame-spreading, combustion, and grain deformation processes of unslotted stick propellants. Calculated pressure-time variations during the initial time interval before grain rupture are in reasonable agreement with experimental data obtained from test firings of vented chamber configuration and a 155-mm Howitzer.

TABLE 1

Differences Between the Present Formulation and the Conventional Interior Ballistic Formulation

Subject under Consideration	Present Formulation	Conventional Formulation
Typical grain configuration	* Simulation of a number of typical full-length grains in a bundle of stick propellants. * Each stick is modeled as a separate tue with deformable and combustible walls.	* Simulation of an average grain in a spatial location along a packed bed of granular propellants. * Each bundle is modeled as a continuum characterized by the velocity and stress in the sticks.
Grain deformation and fracture	* Simulated by the unbalanced pressure forces between the internal perforation and external interstitial void region. * Linear viscoelastic constitutive law is used. * Employs dynamic finite-element structure mechanics computational code.	* The process of grain deformation and fracture are not addressed; the longitudinal stresses are considered in the solid-phase momentum equation. * Linear elastic constitutive law is used. * Employs a steady-state relationship between stresses (radial and hoop) and pressures (internal and external)
Grain displacement and acceleration	* The kinematics of the full-length grain is determined from the summation of all forces exerted on the grain.	* The bulk properties of the grains are determined from local momentum balance.
Radiative heat transfer	* Subsurface radiation penetration is allowed and treated by a two-flux model.	* No subsurface radiation penetration is considered.

TABLE 1 (CONTINUED)

Differences Between the Present Formulation and the Conventional Interior Ballistic Formulation

Subject under Consideration	Present Formulation	Conventional Formulation
Type of formulation	* Kinematics and grain deformation are formulated by following the stick (Lagrangian approach); gas-phase properties for internal and external regions are determined from a fixed frame of reference reference (Eulerian approach).	* Both the gas-phase and solid-phase properties are determined from the conservation equations formulated, based upon a fixed frame of reference (Eulerian approach).
Species distribution and location of heat release	* Five groups of species are considered. * Heat release does not have to occur at the site of pyrolysis.	* Gas phase consists of combustion products from ignition and propellant. * Heat release occurs locally at the site of pyrolysis.

3) Propellant grains recovered from the vented-chamber test firings exhibit two types of fracture. Grains in the downstream section shatter into small pieces; those in the upstream portion break with longitudinal slits. Recovered stick bundles from test firings using a set of short-grain segments showed less damage. Many segments recovered from the breech end with initial lengths of 17.8 cm showed no mechanical damage. The grain rupture is believed to be caused mainly by the large pressure differential generated during rapid chamber depressurization. Propellant grains recovered from test firing using half full-bore-length stick bundles showed very little damage.

4) If the ratio of the external interstitial flow cross-sectional area to that of the internal perforation region is large (e.g., 30), the flame-spreading rate over the external surface of a stick-propellant grain could be faster than that over the internal surface. The opposite conditions could occur for low area ratios.

5) Gas-velocity distributions in the internal perforation region could be significantly different from those in the external region. Prior to grain rupture, gases exit the perforation region from both ends.

6) Pressure-wave phenomenon associated with combustion of stick-propellant charges is less than that of conventional multi-perforated granular propellant beds.

7) Stick-propellant grains were found to move very slowly along the cartridge. This could cause the gas temperautre in the breech end to exceed the adiabatic flame temperature by a significant amount due to local compression.

8) Coning phenomena of the internal surfaces on both ends of recovered stick-propellant grains were observed. This suggests the importance of erosive burning in the combustion of stick propellant bundles.

List of Publications

K. K. Kuo, "Potential Mechanisms Involved in Stick Propellant Combustion Processes," JANNAF Workshop, July 12-13, 1983, ARRADCOM-Dover.

Kuo, K. K., Hsieh, K. C., and Athavale, M. M., "Modeling of Combustion Processes of Stick Propellants via Combined Eulerian-Lagrangian Approach," Proceedings of the Eighth International Symposium on Ballistics, Oct. 1984, pp. I-55 to I-68.

Athavale, M. M., Hsieh, K. C., Hsieh, W. H., Char, J. M., and Kuo, K. K., "Interaction of Flame Spreading, Combustion, and Fracture of Single-Perforated Stick Propellants Under Dynamic Conditions," 10th International Colloquium on Dynamics of Explosions and Reactive Systems, 1985, also published in Dynamics of Reactive Systems, Part II: Modeling and Heterogeneous Combustion, AIAA Progress Series, Vol. 105, edited by J. R. Bowen, 1986, pp. 267-290.

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Hsieh, K. C. and Kuo, K. K., "Numerical Simulation of Combustion Processes of Mobile Stick-Propellant Bundles," 23rd JANNAF Combustion Meeting, Hampton, VA, Oct. 20-24, 1986, CPIA Publication 457, Vol. 1, pp. 295-306.

Char, J. M. and Kuo, K. K., "Combustion and Rupture of Single-Perforated Stick Propellants," Chemical and Physical Processes in Combustion, Fall 1986 Technical Meeting of the Eastern Section of the Combustion Institute, San Juan, Puerto Rico, Dec. 15-17, 1986, pp. 12-1 to 12-4.

Hsieh, W. H. and Kuo, K. K., "Numerical Simulation of Erosive Burning of Unslotted Stick Propellants," Chemical and Physical Processes in Combustion, Fall 1986 Technical Meeting of the Eastern Section of the Combustion Institute, San Juan, Puerto Rico, December 15-17, 1986, pp. 13-1 to 13-4.

Char, J. M. and Kuo, K. K., "Study of Combustion Processes of Single-Perforated Stick Propellants," AIAA/ASME/SAE/ASEE 23rd Joint Propulsion Conference, San Diego, California, AIAA Paper No. AIAA-87-2029, June, 1987.

Hsieh, W. H., Char, J. M., Zanotti, C., and Kuo, K. K., "Erosive Burning Study of Stick Propellants," AIAA/ASME/SAE/ASEE 23rd Joint Propulsion Conference, San Diego, California, AIAA Paper No. AIAA-87-2032, July, 1987.

Hsieh, W. H., Zanotti, C., Char, J. M., and Kuo, K. K., "Measurement of Burning Rates of NOSOL-363 Propellants Under Cross-Flow and Strand Burner Conditions Using Real-Time X-ray Radiography," 24th JANNAF Combustion Meeting, Monterey, California, October 5-9, 1987.

Hsieh, W. H., Char, J. M., and Kuo, K. K., "Study of Erosive and Strand Burning of Stick Propellants Part I: Measurements of Burning Rates and Thermal Wave Structures," submitted for publication in the Journal of Propulsion and Power.

Hsieh, W. H., and Kuo, K. K., "Study of Erosive and Strand Burning of Stick Propellants Part II: Theoretical Model and Simulation of Erosive Burning Processes," submitted for publication in the Journal of Propulsion and Power.

Scientific Personnel Supported by this Project and Degrees Awarded

Prof. K. K. Kuo

Mr. M. Athavale, M.S. Degree, June 1985

Dr. K. C. Hsieh, Ph.D. Degree, May 1987

Dr. W. H. Hsieh, Ph.D. Degree, August 1987

Dr. J. M. Char, Ph.D. Degree, December 1987

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