Tripoli Rocketry Association, Inc., et al. v. ATF
Civil Action No. 00-273

ATTACHMENT #6

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Burn Rates of Common Materials Compared to Ammonium Perchlorate Composite Propellant

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Abstract:

The linear burn rates of several common materials, including paper, cotton, plastic, and straw, were determined and compared to the burn rate of typical ammonium perchlorate composite propellant (APCP). In all cases the burn rates of the common items were found to be comparable to, or greater than, the burn rates of typical APCP formulations.

Background

In chemistry, the rate of a reaction is expressed as change in the amount of reactant or product per unit time. The most common unit for ordinary chemical reactions is moles per liter per second or molar per second ($M\ s^{-1}$). For rocket propellant, however, burn rates ordinarily are expressed as the length of propellant burned per unit time, i.e., meters per second or inches per second ($in\ s^{-1}$), partly because it is that unit of length per unit time that determines chamber pressure and other ballistic properties of the propellant.

To a first approximation the burn rate of a propellant is governed by Vielle's law, an expression that can be seen to be similar to the general rate law for a chemical reaction:

Vielle's law: $\text{Rate} = a P^n$

General rate law: $\text{Rate} = k [A]^n [B]^m [C]^p \ldots$

In the expression for Vielle's law, a is the burn rate coefficient, and is analogous to the rate constant of a chemical reaction; P is chamber pressure; and n is the burn rate exponent, analogous to the order of a reaction. In practice, propellant burn rates are most often expressed in engineering units of inches per second and pressure in lb in^{-2}. Accordingly, n also has units of inches per second.

In chemical reactions, the rate constant and the order of the reaction ordinarily must be determined empirically, by experiment; they cannot be accurately predicted. Likewise, a and n are empirically-determined quantities that are found by testing the propellant in question and are specific for that propellant. Although both a and n can vary somewhat for different rocket propellants, the most common type of composite rocket propellant, ammonium perchlorate composite propellant (APCP), generally exhibits values of a around 0.01 – 0.05, and values of n around 0.3 – 0.5. The typical burn rate of APCP is on the order of 0.1 – 0.5 in s^{-1} at normal operational pressures of ca 1000 psi, with the burn rate decreasing as chamber pressure decreases. At atmospheric pressure, the burn rate of most APCP formulations decreases to around 0.05 in s^{-1} or less.

It is intuitively apparent that the burn rate of APCP appears to be quite similar to the burn rate of some common, everyday items such as paper. The purpose of this work was to measure the burn rates of such everyday items, and to compare those burn rates to the typical burn rate reported for APCP.

Experimental

Materials selected for examination included: Ordinary white 24 lb basis office paper, newsprint, paper towels, wax paper, polyethylene sheet, agricultural straw, and

cotton batting. All materials except the straw were cut into 8½ x 11 sheets for uniformity. Straw was bound with twist-ties into bundles approximately 1" in diameter. Newsprint was tested both as flat sheets and crumpled into a rough lengthwise (11" long) cylinder. The rationale for the latter was that crumpled newsprint is commonly utilized as a fire-starting material for fireplaces and charcoal grilling.

The material under test was placed on a simple metal grate and a small propane torch was used to ignite the material at one end, heating just long enough to insure ignition of that edge. The time required for the flame front to first reach the other end of the material was measured, and the burn rate determined by dividing the length burned (11") by the burn time. For most materials, 16 replicate determinations were performed. The average burn rate and the standard deviation were calculated.

For comparison purposes, two commercial APCP formulations from Industrial Solid Propulsion, Inc. were selected. One propellant is used both as a delay-charge formulation and as a propellant in the company's commercial motors, and is designated #8021D (AKA "Blackjack" propellant, standard specific impulse 154 seconds). The other propellant selected for comparison is the company's highest-performance product, designated #8843 (standard specific impulse 263 seconds). These propellants were not physically tested for this project; instead, the burn rates of these two propellants were determined from the company's published propellant characterization data. (Industrial Solid Propulsion Inc. Product Portfolio).

Results and Discussion

TABLE 1: Burn Times and Burn Rates	Average burn time, 8 1/2 x 11 sheet	Average burn rate, in/second	Standard deviation, in/second
White office paper, 24 lb (Office Depot)	42.8	0.26	0.045
Newsprint, sheet	28.4	0.39	0.223
Newsprint, crumpled	21.2	0.52	0.414
Paper towels (Kroger)	36.9	0.30	0.068
Wax paper (Cut-Rite)	13.3	0.83	0.374
Polyethylene sheet, clear, 4 mil (Lowe's)	80	0.14	**
Agricultural straw, 1" bundles	276	0.04	**
Cotton crib/craft batting 1/8" (Morning Glory brand)	62.7	0.18	0.047
APCP formulations at 1000 psi			
ISP #8021D		0.11	
ISP #8843		0.33	

** See text for explanation.

The experimental results are presented in Table 1. With the exception of straw and polyethylene sheet, all the tested materials tested burned at a rate exceeding that of the #8021 propellant formulation. Both straw and polyethylene sheet are noteworthy because both tended to go out after ignition; polyethylene tended to melt rather than burn. Because of this tendency, only two successful determinations each of the burn rates of straw and polyethylene sheet were performed. Thus, the numeric burn rates of these two materials should be viewed with caution.

Some of the "flat" materials exhibited an "edge effect" in which the flame front advanced somewhat more rapidly along an edge than at the center. The edge effect was least pronounced with wax paper, which burned fairly uniformly.

It should be noted that the propellant formulations' burn rates are reported in Table 1 at 1000 psi, which is the standard pressure for comparison of solid propellants, and is a reasonable operating pressure for a rocket motor. Those same propellants burnt at atmospheric pressure will burn much more slowly. #8021D burns at approximately 0.03" per second at atmospheric pressure, and #8843 is slightly faster, approximately

0.06" per second. Thus, all of the tested materials at atmospheric pressure—including the slowest-burning material, straw—would burn faster than #8021D at atmospheric pressure, and all but straw would burn more rapidly than #8843 at atmospheric pressure.

By the same token, all of the tested materials would be expected to burn more rapidly at elevated pressure. Actual measurements at elevated pressures were not made for this study because facilities for such measurements were not available. Thus, a comparison of all the materials at elevated pressure would provide the same general result—most or all of the common materials would burn at a higher rate than APCP.

Conclusion

Some common combustible materials can be shown to burn at a rate that equals or exceeds the rate of combustion of APCP in its normal use.

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EDUCATION

1989 Ph.D., Analytical Chemistry, Virginia Polytechnic Institute, Blacksburg.
Dissertation: "Some Aspects of Rapid Analysis of Coal Slurries by Direct Current Plasma Emission Spectrometry", under Gary L. Long

1981 M.S., Analytical Chemistry, University of Georgia, Athens.
Thesis: "Design and Evaluation of a Double Beam-in-Time Photoacoustic Spectrometer", under Geoffrey N. Coleman

1977 B.S., Chemistry, St. Francis College, Loretto, PA

EMPLOYMENT

1995- Associate Professor, Murray State University
1988-95 Assistant Professor, Murray State University. Tenure awarded 1994

Undergraduate and graduate courses I have taught include:

- Consumer chemistry (non-science majors) [MSU course: CHE 101]
- General/Organic/Biochemistry (nursing/tech) [CHE 105/106]
- General chemistry, for majors and pre-professionals [CHE 201/202]
- Analytical chemistry (quantitative analysis) [CHE 305]
- Basic instrumental analysis (non-calculus background) [CHE 352]
- Glassblowing [CHE 545]
- Instrumental analysis at both undergraduate and graduate levels [CHE 519/672/689]

I have directed or assisted over two dozen undergraduate students in research projects and independent study in chemistry. Two graduate students have completed M.S. degrees in chemistry under my direction, and I have served on graduate committees of fourteen M.S. students.

I took a sabbatical leave in Fall 2000 to teach and write at Southern Illinois University at Carbondale.

1986-88 Project Assistant, Department of Chemistry, Virginia Polytechnic Institute
As a graduate student I directed technicians and performed research for Department of Energy project, "Rapid Analysis of Coal Slurries", which led to my Ph.D. dissertation.

1985-86 Teaching Assistant, Virginia Polytechnic Institute
As a graduate student I supervised undergraduate chemistry laboratories in general chemistry.

1979-85 Instructor/Assistant Professor, Cumberland College, Williamsburg, KY.
I taught undergraduate courses in chemistry, including general chemistry, quantitative analysis, instrumental analysis, organic laboratory, and qualitative organic analysis; and I directed undergraduate research.

Tenure was granted and I was promoted to assistant professor in May 1984.

1977-79 Teaching Assistant, University of Georgia
I supervised undergraduate chemistry laboratories in general chemistry and instrumental analysis.

RESEARCH INTERESTS AND SELECTED PUBLICATIONS/PRESENTATIONS

Chemistry education
Solid propellant formulation and characterization.
Fundamental studies of combustion of pyrotechnic mixtures
Diagnostic studies of sample transport and fundamental processes in plasmas
Improved sample introduction in flames and plasmas
Chemical instrumentation and method development

2006 **Textbook: *Chemistry for Changing Times* 11th edition, John Hill and Doris Kolb (T. W. McCreary, Contributing Author) Prentice Hall, ISBN 0-13-228084-1.** Previous editions of this textbook for "consumer chemistry" (non-science majors) have made it the best-selling consumer-chemistry text worldwide. Dr. Kolb was unable to participate in this edition, so although I was listed as a contributing author, the workload and responsibilities were those of a full coauthor. This textbook was released in June 2006.

2004 **Textbook: *General Chemistry* 4th edition. John Hill, Ralph Petrucci, Terry McCreary, and Scott Perry, Prentice Hall 2005, ISBN 0-13-140313-3.** A general chemistry textbook for science and engineering majors; 1144 pp. Unlike many textbooks with multiple authors, there was no assignment of chapters. Instead, each author fully reviewed each chapter and suggested changes and comments. In addition to normal author's responsibilities I prepared a complete set of PowerPoint presentations—25 chapters, approx. 1200 slides—to accompany the text. I also prepared all annotations—literature citations, demonstration suggestions, clarification commentary—for the Instructor's Annotated Edition. My contract for this textbook extends through a possible 8th edition.

2004 **Instructor's Manual: Instructor's Resource Manual to accompany *General Chemistry* 4th edition; Terry McCreary and Marie Hankins, Prentice Hall 2005, ISBN 0-13-140316-8.** 397 pp. I was solely responsible for revising and updating this manual, completed over a period of just seven weeks.

2002 **Textbook: *Chemistry: An Integrated Approach*, 3rd edition, John Hill and Ralph Petrucci (T. W. McCreary, Contributing Author) Prentice Hall 2002, ISBN 0-13-098471.** Contributions included special essays, art review and construction of macro-micro figures, review of all 25 chapters of the text itself, development of new problems, construction of the index, and review of the

website questions (approximately 1500 multiple-choice questions with individualized feedback to each response).

2000 **Monograph: *Experimental Composite Propellant*, T. W. McCreary 2000. 243 pp** A monograph on the technical and practical aspects of preparation, properties, and characterization of composite ammonium perchlorate solid rocket propellant and simple motor construction.

1996 "Catalysis of PSAN-Based Composite Propellant", Crystal Daniels, Amber Walker, and T. W. McCreary, presented at Kentucky Academy of Science, Frankfort, KY.

1996 "Comparison of Gasometric and Gravimetric Determination of Magnesium in Propellant Mixtures", Kim Newman and T. W. McCreary, presented at Kentucky Academy of Science, Frankfort, KY.

1994 "Nonrefractory Slurries in the ICP: Size Control and Recovery" Chuenyuan Chen and T. W. McCreary, Applied Spectroscopy 48, 410 (1994)

1991 ***Laboratory Techniques and Experiments In Chemistry***, General Chemistry Laboratory Manual, MSU University Press. Originally published in 1991, revised in 1999 and in 2002. This manual for first-semester majors-level chemistry has been used for fourteen years at Murray State.

SELECTED GRANTS

2003 Principal Investigator for "PARTNERSHIPS IN PROPULSION: Research, Design and Testing of Alternative Rocket Propellants and Motors", Research Incubation Grant for $10,000, funded in December 2003.

2001-03 Co-Principal Investigator for "Establishing New Traditions in Chemistry at Murray State University". National Science Foundation CCLI-Adaptation and Implementation Grant for $307,960.

1988-2004 Eight grants from the Committee for Institutional Studies and Research, Murray State University, for propellant research and study, totaling approximately $16,000.

SELECTED SERVICE/PROFESSIONAL ACTIVITIES

- Faculty advisor for SAACS, the Student Affiliates of the American Chemical Society at Murray State University, five years. Included trips to the Pittsburgh Spectroscopy Society Conference; various social activities, picnics, parties, and pot-lucks; two Area Collegiate Chemistry Meetings hosted by MSU SAACS and three hosted by U.T. Martin; attendance at KLS-ACS; aid to the MSU Scholarship Tournament Examination. During my service, MSU-SAACS was awarded its first Outstanding Chapter award.

- One year as President-Elect and one year as President of the Kentucky Lakes Section of the American Chemical Society (KLS-ACS).
- Two years as Senator-At-Large, MSU Faculty Senate; currently chair of the Handbook and Personnel committee of the Faculty Senate.
- Four years as member of the Board of Directors of the Tripoli Rocketry Association, a 501(c)3 not-for-profit organization promoting noncommercial rocketry worldwide. www.tripoli.org. We have been awarded three small grants under my directorship.
- Preparation and grading of the MSU annual Chemistry Scholarship Tournament Examination for fourteen years.
- Two times Special Awards Judge for Chemistry at the International Science and Engineering Fair in Louisville.
- Four years moderator in the Science Bowl at MSU.
- Five years as the faculty advisor to the MSU Humanist Student Association, which meets every other week; I have attended almost all of the meetings.
- Two years member of the collegiate curriculum committee.
- One semester as a replacement collegiate representative to the University Tenure Committee.
- As Technical Editor for the *Journal of Pyrotechnics* I have reviewed eight manuscripts submitted for publication.
- I carried out a number of *pro bono* consulting tasks for various companies including Estron Chemical, GAF, Aerotech, BioMicro Systems, and others including two attorneys. Most involved spectroscopic analysis (IR, AA, or DCP).
- To date I have met with 86 prospective chemistry students to inform them of the department and provide departmental tours.

PERSONAL

- DOB 13 October 1955
- Address: 1606 Wiswell Road, Murray, KY 42071. (270)759-1552
- Married (Geniece); two children (April Yvette, 15; Alycia Corinne, 18)
- Hobbies and Interests: Most involve "making things". Astronomy and telescope making, cooking, gardening, rocketry, pyrotechnics, metalworking and foundry, woodworking, carpentry and house renovation, reading. I have had articles published in *Projects in Metal*, *High Power Rocketry*, and *Extreme Rocketry* magazines.