

# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 24 March 1999	3. REPORT TYPE AND DATES COVERED Conference Proceedings	
4. TITLE AND SUBTITLE Int'l Workshop on Errors and Noise in Energ. Material Combustion Experiments			5. FUNDING NUMBERS F61775-99-WF015	
6. AUTHOR(S) Conference Committee				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Politecnico di Milano Piazza Leonardo Da Vinci 32 Milan 20133 Italy			8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD PSC 802 BOX 14 FPO 09499-0200			10. SPONSORING/MONITORING AGENCY REPORT NUMBER GSP 99-5015	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (Maximum 200 words)  The Final Proceedings for Int'l Workshop on Errors and Noise in Energ. Material Combustion Exper., 14 March 1999 - 18 March 1999  This is an interdisciplinary conference. Topics include: Measurement techniques of thermophysical and ballistic properties of energetic materials (in particular, solid rocket propellant explosives); how to handle data especially in the presence of sensible errors and noise; and to which extent the obtained data depend on the specific data reduction technique implemented.				
14. SUBJECT TERMS EOARD, Combustion, Rocket Engines, Solid Fuels			15. NUMBER OF PAGES 38	
			16. PRICE CODE N/A	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)  
Prescribed by ANSI Std. Z39-18  
298-102

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**POLITECNICO di MILANO  
DIPARTIMENTO di ENERGETICA**

**International Workshop on  
Errors and Noise in Energetic Material Combustion Experiments**

**Politecnico di Milano, Milano, MI, Italy  
15-16 March 1999**

Second Announcement - 19 February 1999

**Scope**

An international workshop on "Errors and Noise in Energetic Material Combustion Experiments" will be held at Politecnico di Milano on 15-16 March 99 with optional seminar, discussion, and laboratory sessions 17-19 March 99.

The objectives of this workshop are to discuss error and noise problems arising in experiments to measure energetic material properties, and to discuss methods by which those problems can be avoided, minimized, or used to extend understanding of the material properties and behavior.

Previous workshops in this series (Combustion Instability in 1997 and Property Measurements in 1998) have highlighted the extreme importance of wider and more accurate experimental knowledge of the fundamental thermophysical and ballistic properties of energetic materials such as solid rocket propellants. The 1998 workshop, in particular, showed that even the simplest measurements are significantly affected by a variety of errors and noise of electrical, acoustic, structural, and phenomenological origins.

Presentations are sought that document the origins, treatment, and utilization of the error and noise problems encountered in laboratory, motor, or field application environments. Although emphasis will be given to steady measurements and their dependence on the operating environment, nonsteady measurements are also sought because they are more susceptible to error and noise problems.

Topics of particular interest include:

- Thermophysical and ballistic properties of energetic materials;
- Identification or demonstration of new phenomena associated with the combustion of energetic materials;
- New or improved experimental, diagnostic measurements, or data analysis techniques;
- Data analysis procedures to extract results obscured by sensible errors and background noise;
- Comparisons of results obtained by different specific data handling and analysis techniques; and
- Comparisons of results obtained from experiments using different diagnostic measurements.

Rocket and gun propellant experts, sharing the same basic problems of experimental error in thermophysics, safety, and ageing measurements, are invited to participate.

Workshop presentations are planned for two days, 15-16 March 1999. Specialized seminars and working group activities are planned for the period 17-19 March 1999. Lab facilities are available to conduct simple experiments that can be made to examine points brought out in these discussions.

AQ F00-12-3868

### **Attendance**

Participation by invitation only. A number of qualified researchers from several countries are expected to attend.

### **Speakers**

Each speaker is required to provide a *one page abstract of the presentation* (including title, authors, affiliation) for distribution to all workshop participants.

In addition, each speaker is invited to provide a *copy of the transparencies used for presentation in advance* (at most at the registration time on Monday morning 15 March 99).

The maximum time allowed for presentation is 45 minutes, including at least 20 minutes for questions.

### **Registration**

No fee requested; lunch and coffee breaks courtesy of the sponsors. Pre-Registration by e-mail is recommended (email addresses below); on-site registration will be available Monday 15 March 1999 from 9:00 to 10:00.

### **Sponsors**

We wish to thank the following for their contribution to the success of this conference:

- Politecnico di Milano (PoliMi, Milano, Italy);
- Ministero dell'Università e della Ricerca Scientifica e Tecnologica (MURST, Roma, Italy);
- Agenzia Spaziale Italiana (ASI, Roma, Italy);
- Landau Network Centro Volta (LNCV, Como, Italy);
- European Office of Aerospace Research and Development, Air Force Office of Scientific Research, United States Air Force Research Laboratory;
- United States Army Research Development and Standardization Group (UK), and
- United States Office of Naval Research, Europe.

### **Approximate Exchange Rate**

The exchange rate is about US\$ 1 = 1,700 Lit, but is subject to fluctuations.

### **Lodging**

Arrangements have been made for a block of rooms at the special price of Lit 125,000 (about \$74) for singles and Lit 180,000 (\$106) for doubles, breakfast buffet included, at the nearby

Hotel Gamma (\*\*\*) category)

85 Via Valvassori Peroni, 20133 Milano, MI, Italy

e-mail: htlgamma@tin.it

Ph.: (0039-02) 2641-3152 (eight digits)

NB: 0 is needed for the area code

Fax: (0039-02) 264-0255 (seven digits)

NB: 0 is needed for the area code

Reservations have to be made by Workshop attendees directly with Hotel Gamma by 1 March 99, preferably by fax or e-mail. Reservations received after this date might not be accepted. Please specify the date (and expected time) of arrival and departure, and make sure to mention "Workshop DeLuca" in your reservation to qualify for the above special price.

### Travel

**ARRIVAL.** Attendees flying from USA, Russia, and Japan will arrive to Malpensa airport (northwest of Milan), attendees flying from most European countries will arrive to Linate Airport (southeast of Milan). Attendees traveling by train from Europe will very likely arrive at "Stazione Centrale" (Central Rail Road Station). Attendees traveling by car are invited to go directly to Hotel Gamma (East of Milan) by exiting "tangenziale est" (eastern belt highway) at Lambrate or Rubattino or Linate.

Shuttle buses (just a regular size bus, clearly marked Malpensa Shuttle or Linate Shuttle) are available from both airports for several destinations. Stazione Centrale is the recommended *direction* from both arrival airports. A small section of Stazione Centrale serves also as Air Terminal and provides subway connections to all directions.

**FROM MALPENSA AIRPORT.** The Malpensa shuttle bus leaves every 30 minutes for Stazione Centrale. The ticket has to be bought before entering the bus, at the current cost of Lit 13,000 (less than \$ 8). Signs show the way. The ride takes 50 minutes (under normal traffic conditions). There might be an intermediate stop, but the crowd will get out at Stazione Centrale.

From Stazione Centrale, a taxi to Hotel Gamma is the best option; the cost should be less than \$ 20. For more daring people, a subway ride on Line 2 (the "green" line) is a cheaper alternative: the exit is (only four stops from Stazione Centrale) and the ticket costs less than 1 \$.

**FROM LINATE AIRPORT.** Also attendees arriving to Linate airport are advised to use the shuttle bus toward Stazione Centrale, but please remember to get out at Stazione Lambrate (the first and only intermediate stop before the final stop at Stazione Centrale). The Linate shuttle bus leaves every 20 minutes for Stazione Centrale. The ticket can be bought directly from the driver on the bus, at the current cost of Lit 4,500 (less than \$ 3). Signs show the way. Anyway, after exiting the custom area, get out into the traffic area and parking lots (no other option is available). You will see many taxis and buses at most 100 m far from you (depending on the exit door). The bus is clearly marked; look also for the sign STAM (Societa' Trasporti Aeroporti Milanesi) and direction "Stazione Centrale". The ride takes 15 minutes (under normal traffic conditions). The Lambrate stop is less than 100 m far from Hotel Gamma. A more expensive option is a taxi ride directly from Linate to Hotel Gamma; the cost should be around \$ 20.

Should you forget to get out at Stazione Lambrate, you will necessarily reach Stazione Centrale. From Stazione Centrale, a taxi to Hotel Gamma is the best option; the cost should be less than \$ 20. For more daring people, a subway ride on Line 2 (the "green" line) is a cheaper alternative: the exit is (only four stops from Stazione Centrale) and the ticket costs less than 1 \$.

**FROM STAZIONE CENTRALE.** From Stazione Centrale, a taxi to Hotel Gamma is the best option; the cost should be less than \$ 20. For more daring people, a subway ride on Line 2 (the "green" line) is a cheaper alternative: the exit is (only four stops from Stazione Centrale) and the ticket costs less than 1 \$.

### **Local Transportation**

The subway is the quickest way to move around once in town. The subway sign is a relatively big (say, 50x50 cm), well visible red sign which reads "M" or "MM" (Metropolitana Milanese). There are 3 lines (No. 1 or Red, No. 2 or Green, No. 3 or Yellow respectively from the color of the internal signs).

Please avoid private people offering a car ride, use only licensed taxis (yellow or white cars, with the sign TAXI well visible). This is particularly true at Stazione Centrale and Linate. Also, be aware of the fact that luggages require an extra fee (Lit 500 /piece) not included in the price indicated by the taximeter; similarly, all rides from Linate airport (around Lit 5000) and late evening or Sunday rides (around Lit 2000) require an extra fee. All charges are clearly indicated in several languages inside all licensed taxis.

### **Useful Internet Information**

- For Malpensa airport, please consult the site:

[http://travel.epicurious.com/travel/c\\_planning/06\\_airports/eur/milanmpa.html](http://travel.epicurious.com/travel/c_planning/06_airports/eur/milanmpa.html)

- For Linate airport, please consult:

[http://travel.epicurious.com/travel/c\\_planning/06\\_airports/eur/milanlte.html](http://travel.epicurious.com/travel/c_planning/06_airports/eur/milanlte.html)

- For general information about "How to reach Politecnico di Milano" (only in italian) please consult:

<http://www.polimi.it/storia/sedi/comerag.html>

- For maps of the subway lines, please consult:

<http://www.polimi.it/storia/sedi/comerag.html>

- For detailed maps of Milano, please consult:

<http://www.polimi.it/storia/sedi/comerag.html>

- Specific maps of the zone between Central Railway Station and "Citta' Studi" (where Politecnico is located) are available at the site:

<http://www.polimi.it/cgi-bin/htimage/IMG/gen2.conf?561,293> .

- For information about the weather in Italy, please consult the site:

[http://travel.epicurious.com/travel/c\\_planning/99\\_weather/intro.htm](http://travel.epicurious.com/travel/c_planning/99_weather/intro.htm)

### **Climate**

Expected day temperature in the range 10 - 15 °C.

### **Miscellaneous**

- ✓ Language: working language is English, no simultaneous translation will be provided.
- ✓ Service & tip: at restaurants, hotels, taxis, etc. service cost is always included, tipping is occasionally given for specially well rendered services.
- ✓ Electricity: 220 V with European type sockets.
- ✓ Credit cards: many shops and most hotels accept major international credit cards.

### **Social Dinner**

In a typical Italian restaurant on Tuesday 16 March 99 at 21:00. Fixed price: 60,000 Lit (about 35 \$) per person.

### **Emergency**

For any urgent matter, please:

- contact the Organizing Committee at the registration desk
  - for voice messages call: + (0039-02) 2399-3871, 2399-3872, 2399-3877, 2399-3912
  - for fax messages dial: + (0039-02) 2399-3940
  - for e-mail messages use: [Menalli@clausius.energ.polimi.it](mailto:Menalli@clausius.energ.polimi.it)  
or: [DeLuca@icil64.cilea.it](mailto:DeLuca@icil64.cilea.it)
- 

For any further information, please contact:

#### *Mr. Andrea Menalli*

Laboratorio di Termofisica

Dipartimento di Energetica, Politecnico di Milano

32 Piazza Leonardo da Vinci, 20133 Milano, MI, Italy.

e-mail address: [Menalli@clausius.energ.polimi.it](mailto:Menalli@clausius.energ.polimi.it)

Fax: (0039-02) 2399-3940 Dept Campus Leonardo

Ph.: (0039-02) 2399-3871, 2399-3872, 2399-3877 lab.

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#### *Prof. Luigi De Luca*

Dipartimento di Energetica, Politecnico di Milano

32 Piazza Leonardo da Vinci, 20133 Milano, MI, Italy.

e-mail address: [DeLuca@icil64.cilea.it](mailto:DeLuca@icil64.cilea.it)

Fax: (0039-02) 2399-3940 Dept Campus Leonardo

Ph.: (0039-02) 2399-3912 office Campus Leonardo

Ph.: (0039-02) 2399-8512 office Campus Bovisa

Ph.: (0039-02) 2399-3871, 2399-3872, 2399-3877 lab.

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## ERRORS AND NOISE IN ENERGETIC MATERIAL COMBUSTION EXPERIMENTS

Monday, 15 March 1999

Politecnico di Milano, Dipartimento di Energetica

- 08:50 *Registration*  
09:15 **Welcome Address**  
G. Giambelli, Director  
Dipartimento di Energetica, Politecnico di Milano, Italy  
09:25 **Introductory Remarks**  
L. De Luca  
Dipartimento di Energetica, Politecnico di Milano, Italy

### FUNDAMENTALS

B.N. KONDRIKOV chairman

- 09:30 **Effect of Experimental Data Accuracy on the Prediction of the Stability Condition in Solid-Propellant Rocket Motors**  
B.V. Novozhilov  
Institute of Chemical Physics, Academy of Sciences, Moscow, Russia  
10:15 **Systematic Errors in Intrusive Concentration and Temperature Measurements in Combustion Chambers**  
R. Pein  
DLR German Aerospace Center, Hardthausen, Germany  
11:00 *coffee break*  
11:30 **Recoil Force Measurement as a Source of Combustion Mechanism Information**  
V.E. Zarko, A.B. Kiskin, V.N. Simonenko, and D.V. Vdovin  
Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia  
12:15 **Ultrasound Measurement Method: Errors, Noise, and Sensitivity**  
F. Cauty  
ONERA, Palaiseau Cedex, France

13:00 *lunch*

### BURNING RATE

R. Pein chairman

- 14:15 **Burning Wave Parameters, Their Pressure and Temperature Sensitivities and Burning Rate Response Functions of Solid Propellants and Monopropellants: Values and Errors**  
A. Zenin and S. Finjakov  
Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia  
15:00 **Industrial Problems in Burning Rate Measurements**  
E. Corsetti  
Fiat Avio - Compensorio BPD, Colleferro, Roma, Italy  
15:30 *Coffee break*  
16:00 **Error Analysis of Burning Rate Measurement Procedure**  
R.O. Hessler and R.L. Glick  
Consultant, Somerville, AL, USA and Consultant, Rensselaer, IN, USA  
16:45 **Laboratory and Small Scale Motor Burning Rate Measurements**  
M. Servieri and L. De Luca  
Dipartimento di Energetica, Politecnico di Milano, Italy  
17:30 *End of session*

Tuesday, 16 March 1999

Politecnico di Milano, Dipartimento di Energetica

08:55 **Introductory Remarks**

L. De Luca

Dipartimento di Energetica, Politecnico di Milano, Italy

**BURNING EXPERIMENTS**

**B.V. NOVOZHILOV** chairman

09:00 **Energetic Material Combustion Experiments on Propellant Formulations Containing Prilled ADN**

A.L. Ramaswamy

University of Maryland, Maryland, USA

09:45 **Burning and Ignition Peculiarities of the Systems on the Base of AN, HAN and ADN**

B.N. Kondrikov, V.Yu. Egorshv, V.E. Annikov, and L. De Luca

Mendeleev University of Chemical Technology, Moscow, Russia

10:30 **Peculiarities of Using Microwave Technique in Solid Combustion Studies**

V.E. Zarko, D.V. Vdovin, and V.V. Perov

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

11:15 *coffee break*

11:45 **Ignition of Energetic Materials at Fast Compression of Gas Inclusion. Scatter of Measurements and Unification of Results**

B.N. Kondrikov

Mendeleev University of Chemical Technology, Moscow, Russia

12:30 **About Combustion phenomena of Double-Base Propellant Under Conventional- and Plasma-Ignition Conditions**

B. Baschung and D. Grune

French-German Research Institute Saint-Louis, Saint-Louis, France

13:15 *lunch*

**SESSION 04**

**R.L. GLICK** chairman

14:15 **Filtering Techniques for Combustion Test Data Analyses**

R.O. Hessler

Consultant, Somerville, AL, USA

15:00 **Errors and Noise in Laser Recoil Measurements**

F. Cozzi, A. Balasini, and R.O. Hessler

Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

15:45 *Coffee break*

16:15 **Sampling and Characterization of Condensed Combustion Products of Metalized Propellants. Problems and Perspectives**

O.G. Glotov, V.E. Zarko, V.V. Karasev, and A.D. Rychkov

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

16:45 **Numerical Modeling of Composite Propellant Combustion**

F. Miccio

Istituto di Ricerche sulla Combustione - C.N.R., Napoli, Italy

17:15 **Concluding Remarks**

17:30 **Closure of workshop**

20:30 *Farewell Dinner*

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Wednesday, 17 March - Thursday, 18 March - Friday, 19 March 1999

Politecnico di Milano, Dipartimento di Energetica  
Laboratorio di Termofisica

**Specialized Seminarars and Working Group Activities**

Lab facilities are available to conduct simple experiments that can be made to examine points brought out in these discussions.

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Wednesday, 17 March 1999

Politecnico di Milano. Laboratorio di Termofisica

08:55 **Introductory Remarks**

L. De Luca

Dipartimento di Energetica, Politecnico di Milano, Italy

**ACOUSTIC DIAGNOSTICS IN COMBUSTION**

**L. De Luca chairman**

09:00 **Underwater Burning Rate Measurements by Microphones - 1**

S. Rampichini, D. Ruspa, and L. De Luca

Dipartimento di Energetica, Politecnico di Milano, Italy

10:30 *coffee break*

11:00 **Underwater Burning Rate Measurements by Microphones - 2**

S. Rampichini, D. Ruspa, and L. De Luca

Dipartimento di Energetica, Politecnico di Milano, Italy

12:30 *lunch*

14:00 **Energetic Material Testing by Ultrasounds - 1**

F. Cauty

ONERA, Palaiseau Cedex, France and Dipartimento di Energetica, Politecnico di Milano, Italy

15:30 *Coffee break*

16:00 **Energetic Material Testing by Ultrasounds - 2**

F. Cauty

ONERA, Palaiseau Cedex, France and Dipartimento di Energetica, Politecnico di Milano, Italy

17:30 End of Session

Thursday, 18 March 1999

Politecnico di Milano, Laboratorio di Termofisica

08:55 **Introductory Remarks**

L. De Luca

Dipartimento di Energetica, Politecnico di Milano, Italy

**BURNING EXPERIMENTS**

**L. De Luca chairman**

09:00 **Radiative Heat Feedback Measurements by Microcalorimeter - 1**

G. Tussiwand and M. Milazzo

Dipartimento di Energetica, Politecnico di Milano, Italy

10:30 *coffee break*

11:00 **Radiative Heat Feedback Measurements by Microcalorimeter - 2**

G. Tussiwand and M. Milazzo

Dipartimento di Energetica, Politecnico di Milano, Italy

12:30 *lunch*

14:00 **Energetic Material Testing by Ultrasounds - 3**

F. Cauty and L. Galfetti

ONERA, Palaiseau Cedex, France and Dipartimento di Energetica, Politecnico di Milano, Italy

15:30 *Coffee break*

16:00 **Energetic Material Testing by Ultrasounds - 4**

F. Cauty and L. Galfetti

ONERA, Palaiseau Cedex, France and Dipartimento di Energetica, Politecnico di Milano, Italy

17:30 End of Session

Friday, 19 March 1999

Politecnico di Milano. Laboratorio di Termofisica

08:55 **Introductory Remarks**

L. De Luca

Dipartimento di Energetica, Politecnico di Milano, Italy

**LASER SUSTAINED COMBUSTION**

**L. De Luca chairman**

09:00 **Laser Recoil Experiments - 1**

F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler

Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

10:30 *coffee break*

11:00 **Laser Recoil Experiments - 2**

F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler

Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

12:30 *lunch*

14:00 **Laser Recoil Experiments - 3**

F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler

Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

15:30 *Coffee break*

16:00 **Laser Recoil Experiments - 4**

F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler

Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

17:30 End of Session



## **ERRORS AND NOISE IN ENERGETIC MATERIAL COMBUSTION EXPERIMENTS**

### **ABSTRACTS**

#### **BURNING EXPERIMENTS**

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##### **Radiative Heat Feedback Measurements by Microcalorimeter**

G. Tussiwand and M. Milazzo

Dipartimento di Energetica, Politecnico di Milano. Italy

##### **Underwater Burning Rate Measurements by Microphones**

S. Rampichini, D. Ruspa, and L. DeLuca

Dipartimento di Energetica, Politecnico di Milano. Italy

# Radiative Heat Feedback Measurements by Microcalorimeters

*G.S. Tussiwand and M. Milazzo*

Dipartimento di Energetica, Politecnico di Milano, Milan, Italy

Changes in the steady burning rates of solid rocket propellants caused by radiant heating have been investigated since the 60's both in the US and former Soviet Union. As a matter of fact, radiant heat is responsible for increased burning rates of both small and full scale motors with respect to strand burner values. Therefore, for motor applications burning rate data obtained from strand burners need to be corrected by a scale factor. Several efforts have been made to propose theoretical models (e.g.: Summerfield, Ibiricu and Williams, Brewster and Son) and/or develop diagnostic techniques to measure the natural thermal radiation emitted by the flame of burning propellant samples (e.g.: Zenin, Beyer). At Laboratorio di Termofisica (LTF), combustion of propellant strands under a laser beam has already been tested. We are now trying to measure the natural radiant flux emitted by burning propellant sample for nonaluminized and aluminized AP-HTPB propellants. The radiant flux will be measured using a thin copper disk as sensing element, following a technique first used by Zenin. Measurements, however, are affected by convective and radiative heat losses. Simulations with a first order concentrated parameter model show that convective losses occur even at very low radiant fluxes (such as  $0.1 \text{ W/cm}^2$ ), while radiative losses become important at higher heat fluxes. Thus, a calibration procedure taking into account convective losses seems necessary to improve the quality of measurements and increase the sensibility of the calorimeter. Attempts to limit the errors produced by the unavoidable, nonlinear radiative losses, particularly important when burning aluminized propellant samples, are discussed.

# Underwater Burning Rate Measurements by Microphones

*S. Rampichini, D. Ruspa and L. De Luca*  
Dipartimento di Energetica, Politecnico di Milano, Milano, Italy

Samples of ammonium perchlorate (AP) - based composite solid propellant are ignited and burned in a chamber filled with water and pressurized by a gas (air or nitrogen). The acoustic signal of the combustion process is picked up by two microphones: one submerged in water and the other located in the pressurized gas volume. This signal is first analyzed in the time domain to obtain preliminary information about the mean (quasi-steady) burning rate. The different components of the signal are then resolved in their frequencies using a FFT. Since frequencies are observed to change in time these are conveniently studied through a Spectrogram (or Sonagram) technique. Notches cut on the propellant strand are usually revealed by the spectrogram. In principle, this allows to deduce more accurate quasi-steady burning rate measurements than those obtained in standard acoustic burners. Transient combustion phenomena as well, including effects due to propellant heterogeneity, appear to be revealed by the collected spectrograms. In particular, extinction phenomena and ignition delays are discussed.



## **ERRORS AND NOISE IN ENERGETIC MATERIAL COMBUSTION EXPERIMENTS**

### **ABSTRACTS**

Monday, 15 March 1999

#### **FUNDAMENTALS**

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**Effect of Experimental Data Accuracy on the Prediction of the Stability Condition in Solid-Propellant Rocket Motors**

B.V. Novozhilov

Institute of Chemical Physics, Academy of Sciences, Moscow, Russia

**Systematic Errors in Intrusive Concentration and Temperature Measurements in Combustion Chambers**

R. Pein

DLR German Aerospace Center, Hardthausen, Germany

**Recoil Force Measurement as a Source of Combustion Mechanism Information**

V.E. Zarko, A.B. Kiskin, V.N. Simonenko, and D.V. Vdovin

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

**Ultrasound Measurement Method: Errors, Noise, and Sensitivity**

F. Cauty

ONERA, Palaiseau Cedex, France

#### **BURNING RATE**

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**Burning Wave Parameters, Their Pressure and Temperature Sensitivities and Burning Rate Response Functions of Solid Propellants and Monopropellants: Values and Errors**

A. Zenin and S. Finjakov

Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia

**Industrial Problems in Burning Rate Measurements**

E. Corsetti

Fiat Avio - Compensorio BPD, Colleferro, Roma, Italy

**Error Analysis of Burning Rate Measurement Procedure**

R.O. Hessler and R.L. Glick

Consultant, Somerville, AL, USA and Consultant, Rensselaer, IN, USA

**Laboratory and Small Scale Motor Burning Rate Measurements**

M. Servieri and L. DeLuca

Dipartimento di Energetica, Politecnico di Milano, Italy

# Effect of Experimental Data Accuracy on the Prediction of the Stability Condition in Solid-Propellant Rocket Motors

*B.V. Novozhilov*

Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia

To predict the stability condition of a steady-state combustion regime in a solid-propellant rocket motor one should know so called propellant response function to oscillatory pressure. There are two ways to obtain these functions: firstly, from a direct experiment, for example, in T-burner, and, secondly, by the help of a theory. In this report, only the second way is discussed. Because any theory involves into

consideration some experimental data, the influence of experimental data errors is discussed on the accuracy of the response functions obtained theoretically.

Consideration is presented in the framework of the Zel'dovich-Novozhilov theory. The explicit expression of the propellant burning rate, burning temperature, and gas velocity response functions to oscillatory pressure are investigated to reveal the general properties of the solid propellant response functions:

- a. They have a great sensitivity to propellant parameters at frequencies close to the natural frequency.
- b. There is also a great sensitivity to small changing propellant model.

The accuracy of the stability condition of a steady-state combustion regime in a solid-propellant rocket motor is estimated taking into account also the motor nozzle response function to oscillatory pressure.

The result of the presented consideration may be formulated in the following form. The theoretical values of both the response functions and the stability condition might be obtained with reasonable errors provided that steady-state experiments have rather high accuracy.

# Systematic Errors in Intrusive Concentration and Temperature Measurements in Combustion Chambers

*R. Pein*

DLR - German Aerospace Center, 74239 Hardthausen, Germany

Measurements of species, temperature and velocity distribution in combustion chambers are of great importance in aerospace applications. The exact knowledge of these data is necessary for determination of reaction zones, mixing and combustion efficiencies as well as pollutants in propulsion systems like rockets and ramjets. The results should lead to a better understanding of the combustion process, to an improved design of the propulsion system under investigation, and to a validation of existing computer codes. This should also reduce the necessary number of test runs in test facilities and finally decrease the costs of such operations.

The typical systematic errors which are made during intrusive concentration and temperature measurements in combustion chambers are illustrated. Besides isokinetic and representative sampling the most important factor is the rapid quench of the combustion gases and freezing of the composition of the combustion products. This is studied in detail by means of a simple analytic heat transfer model for the sampling probe. Plug flow and constant mean properties of the gas is assumed as well as constant wall temperature of the probe. The results are expressed in terms of temperature-time histories, temperature profiles and quench rates inside the probe. The dependence on probe diameter, probe mass flow rate, initial temperature and probe wall temperature is discussed. It is shown that only for probes with very small diameters and for low mass flow rates very high initial quench rates up to  $10^{10}$  K/sec can be achieved. The quench process then is completed after a few centimeters probe length. Most sampling probes are too large in diameter. A comparison with chemical reaction rates and literature data shows that it is impossible to quench radical reactions, and, for lower quench rates the measurement errors of minor species like CO and NO are larger than for the main species. Thus this measurement method is limited to not too high combustion temperatures. It is also shown that the temperature of the probe wall has negligible effect on the quench rate. This is of interest for experiments where it is necessary to avoid condensation in the probe by heating the cooling water.

Another important item is the formulation of a mole balance in terms of atom conservation equations in order to validate the results of concentration measurements. Each experimental result should be checked for fulfilling the mole balance. If this is not the case the value should be discarded. A mole balance can also be used for calculating the concentration of a missing component.

The main errors of high-temperature thermocouple measurements, especially the radiation correction are also discussed in detail. A small heat transfer model for the calculation of the radiation correction is evaluated. The results show that the most important parameter is the bead size. For minimization of the radiation losses the bead size should be as small as possible. Another parameter causing some uncertainty is the emissivity of the thermocouple material which is dependent from temperature and composition of the bead. For exact measurements it is also necessary to know at least approximately the chemical composition of the environment in which the temperature measurement is done. Measurement errors can also result from resulting from catalytic effects and high temperature oxidation of thermocouple material.

## **Recoil Force Measurement as a Source of Combustion Mechanism Information.**

*V.E. Zarko, A.B. Kiskin, V.N. Simonenko and D.V. Vdovin*

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

Principles of measurement of recoil force with capacitance and inductive based gages are discussed. Theoretical background of the measurement method is presented. Possible sources of errors in obtaining and treatment of experimental results are analyzed. The errors may appear due to variation of environmental conditions as well as disturbances of combustion because of bad ignition and interaction with inhibiting layer, and due to vibration and electrical noise. Examples of the recoil force records in combustion of different types of solid propellants are presented and discussed. Potentialities of combined measurement of recoil force and dynamic mass loss for deriving new information about combustion mechanism are discussed.

# Ultrasound Measurement Method: Errors, Noise, and Sensitivity

*F. Cauty*

ONERA, Palaiseau Cedex, France

The ultrasound measurement method has been widely applied to determine the burning rate of solid propellants. This contribution is aiming at discussing about the reliability, the accuracy of the method and, finally, of the burning rate evolution deduced from the propagation time variation.

There are, at least, three points of interest.

- the scale factor: the burning rate has to be defined from a tiny sample to a full-scale rocket-motor. It takes place in the framework of the RTO WG27.
- the accuracy of the method including propagation through the condensed phase and the effect of the operating conditions,
- the computation errors related to the derivative function determination and the corrective terms taken into account in the measurement theoretical approach.

What is considered as errors or noise on the measurement as well for the ultrasound echoes evolution as for the burning rate scattered results could be source of information. Examples illustrate the presentation.

# **Burning Wave Parameters, Their Pressure and Temperature Sensitivities and Burning Rate Response Functions of Solid Propellants and Monopropellants: Values and Errors**

*A. Zenin and S. Finjakov*

Semenov Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia

The paper presents results of experimental measurements of burning rates and burning surface temperatures at various pressures and initial sample temperatures of solid monopropellants and propellants. Errors of the measurements are discussed.

Pressure and temperature sensitivities of these parameters are determined on the base of the measurements. Errors of the determinations are estimated.

Burning rate response functions to acoustic pulsations are calculated on the base of the obtained sensitivities. Errors of the calculations are estimated.

Conclusions are made about peculiarities of the obtained sensitivities and burning rate response functions.

# INDUSTRIAL PROBLEMS IN BURNING RATE MEASUREMENT

Corsetti Elisabetta  
FIAT AVIO Compensorio BPD  
Corso Garibaldi 22, 00034 Colleferro, Rome, Italy

Aim of this presentation is to describe the state of art of the burning rate measurement technique performed in industry, and in particular at FIAT AVIO BPD, pointing out the problems arising and discussing some possible solutions which can avoid or minimize them.

As solid propellant burning rate is an essential parameter for the design of solid rocket motors, an error in burning rate evaluation leads to an even worst error in motor performance prediction. So, it is evident how important very accurate burning rate measurement is, even if, for industrial application, the main goal is to achieve the highest reproducibility of it. In fact, repetitive correlation between sub-scale and full-scale motors on burning rate (i.e. scale factor) allows to make motor performance prediction with a higher confidence level.

Three types of industrial sub-scale motors are actually in use at FIAT AVIO BPD for solid propellant burning rate measurement: Crawford bomb, 2 and 6 inch bombs, BARIA bomb (used only in Ariane5 program). Their main measure problems have been taken into account, highlighting the possible causes of dispersions and errors, due both to hardware (i.e. data acquisition system, grain defects, bomb design, etc.) and software (i.e. data reduction method). Corrective actions and proposed improvements are also presented.

# **Error Analysis of Burning Rate Measurement Procedures**

*R.O. Hessler*

Consultant, Somerville, AL, USA

and

*R.L. Glick*

Consultant, Rensselaer, IN, USA

Burning rate measurement procedures are contrasted, using a round robin dataset of simulated motor data having either instantaneous or non-instantaneous burnout as the principal variable. Bias error components of two historical procedures are specifically identified and measured. An iterative least-squares group analysis is shown to improve results from the historical procedures by eliminating the effect of non-neutral pressure-time histories. A two-point measurement procedure is shown to produce bias-free results for these simulations.

# Laboratory and Small Scale Motor Burning Rate Measurements

*M. Servieri and L. DeLuca*

Dipartimento di Energetica, Politecnico di Milano, MI, Italy

The purpose of this paper is to describe the influence of noise in measuring steady burning rates in strand burners and small scale motors. In strand burners, two techniques to measure steady burning rates, fuse wires and video camera, are presented and compared to highlight affinities and differences; the comparison shows that the video technique gives better results. In both cases, it will be pointed out what kind of errors are usually done and how much they affect the final results. In small scale motors, using the "thickness over time method" to measure steady burning rates, web thickness is taken as the nominal one while time interval is detected from the pressure profile. Errors depend on time resolution, and especially on noise polluting pressure profiles. A possible solution to solve this problem is the moving average. An application to real motors is discussed.

Tuesday, 16 March 1999

## **BURNING EXPERIMENTS**

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### **Energetic Material Combustion Experiments on Propellant Formulations Containing Prilled ADN**

A.L. Ramaswamy

University of Maryland, Maryland, USA

### **Burning and Ignition Peculiarities of the Systems on the Base of AN, HAN and ADN**

B.N. Kondrikov, V.Yu. Egorshchikov, V.E. Annikov, and L. DeLuca

Mendeleev University of Chemical Technology, Moscow, Russia

### **Peculiarities of Using Microwave Technique in Solid Combustion Studies**

V.E. Zarko, D.V. Vdovin, and V.V. Perov

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

### **Ignition of Energetic Materials at Fast Compression of Gas Inclusion. Scatter of Measurements and Unification of Results**

B.N. Kondrikov

Mendeleev University of Chemical Technology, Moscow, Russia

### **About Combustion phenomena of Double-Base Propellant Under Conventional- and Plasma-Ignition Conditions**

B. Baschung and D. Grune

French-German Research Institute Saint-Louis, Saint-Louis, France

## **SESSION 04**

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### **Filtering Techniques for Combustion Test Data Analyses**

R.O. Hessler

Consultant, Somerville, AL, USA

### **Errors and Noise in Laser Recoil Measurements**

F. Cozzi, A. Balasini, and R.O. Hessler

Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

### **Sampling and Characterization of Condensed Combustion Products of Metalized Propellants. Problems and Perspectives**

O.G. Glotov, V.E. Zarko, V.V. Karasev, and A.D. Rychkov

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

### **Numerical Modeling of Composite Propellant Combustion**

F. Miccio

Istituto di Ricerche sulla Combustione - C.N.R., Napoli, Italy

# **Energetic Material Combustion Experiments on Propellant Formulations Containing Prilled ADN**

*A.L. Ramaswamy*  
University of Maryland, Maryland, USA

A new formulation composition containing prilled particles of ADN as the oxidizer component was studied. The composition was formulated at NSWC with prills manufactured at Thiokol and CSD. Strand ballistic burn rate data on the propellant formulation showed that the overall performance of the formulation was sensitive to the prill microstructure. Further microstructural characterization of the formulation by ESEM (Environmental Scanning Electron Microscopy) combustion experiments showed that the performance of the composition could further be improved by tailoring the microstructural characteristics of the composition. Such parameters are not revealed by strand burning rate measurements which represent an average or overall measurement and pick up on the localized rate variations as "noise", averaging them out. Microstructural characterization (such as filming the propellant combustion at the highest magnifications and examination of quenched samples) of propellant formulations may thus provide some of the complementary data to the standard propellant characterization measurements to reduce/eliminate measurement errors. Furthermore with prilling the errors are reduced and the performance improved as will be described.

# Burning and Ignition Peculiarities of the Systems on the Base of AN, HAN and ADN

*B.N. Kondrikov, V.Yu. Egorshv and V.E. Annikov*  
Mendeleev University of Chemical Technology, Moscow, Russia

*L. DeLuca*  
Dipartimento di Energetica, Politecnico di Milano, MI, Italy

Ammonium and hydroxylammonium salts of nitrogen containing acids are the well-known bases for formulation of different kinds of energetic materials, particularly rocket and gun propellants. Ammonium nitrate, AN propellants are being known for about a century. Burning of these EM was studied extensively in many laboratories but burning characteristics and mechanism of the steady state and unstable combustion of them are stated till now only very approximately, intensive additive investigation is needed. It is especially true in correspondence to the relatively new energetic materials of this sort, HAN and ADN or to the mixtures of AN with such an energy reach metal as Magnesium that to the contrary of Aluminum is used in the propellants formulations relatively rarely.

In this work we have investigated mechanism of ignition of AN/Mg mixtures by irradiation of CO<sub>2</sub> laser and burning of this compound in comparison with other dry and water impregnated systems containing AN, HAN and ADN. In all cases mechanism of the basic physico-chemical transformations was supposed to be stated and the strong difference in ignition and burning characteristics between compositions containing these oxidizers was elucidated.

The main difference as to the burning characteristics, first of all burning rate and its pressure dependence, is concerned consists in the fact that HAN and ADN systems burn much faster than AN mixtures are found to burn. The great variety of constants in Vielle law is also determined. For instance HAN in the crystal form, first investigated, has pressure exponent as high as 2.5 in the pressure interval of 3 to 50 atmospheres, whereas ADN has only about 0.6, at approximately the same velocity of the combustion wave near the upper border of the interval. At about the same pressure ADN is subjected to burning instability. Correspondingly the big scatter of burning rates may be noted which is changed at still higher pressures with a region of steady combustion with moderate velocity.

At elucidation of the facts and laws this estimated the abundant experimental information concerning some of the others N-acids salts burning is successfully used.

# Peculiarities of Using Microwave Technique in Solid Combustion Studies

*V.E. Zarko, D.V. Vdovin and V.V. Perov*

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

The principles of microwave method for measuring current length of burning propellant sample are described and different schemes of measuring unit are discussed. Theoretical limits of space resolution of devices working in 2-30 mm band are explored. The examples of typical records of 2mm band microwave interferograms in combustion of non-metallized and metallized composite propellants are presented. It is shown that there exist several sources of noise and errors when doing combustion experiments with microwave technique. Accuracy of the length measurement depends on accuracy of the wavelength determination and on disturbances of signal due to inherent roughness of the burning surface and surface curvature because of non-flat ignition. Losses of microwave energy depend on the nature of material and scattering on micro inclusions. Suggestions on proper use of microwave technique for burning rate measurements are formulated.

# Ignition of Energetic Materials at Fast Compression of Gas Inclusions. Scatter of Measurements and Unification of Results

*B.N. Kondrikov*

Mendeleev University of Chemical Technology, Moscow, Russia

Theory of energetic materials (EM) initiation at weak mechanical stimuli was created in the very beginning of 40th. Prof. Yuly Khariton in 1940 solved two problems concerning temperature rise at penetration of a plate into mass of a liquid and at compression of the liquid layer between two polished rigid surfaces. At the same time a young engineer Khariton M. Lavrik found the cardinal solution of a problem of in bore premature explosion of artillery shells. He suggested that initiation of explosive inside the shell was a result of fast compression of a gap at the bottom of the shell filled in by air or a mixture of air and solvent vapors. A little later Prof. Frank P. Bowden in England carried out a series of the shining, eventually classic, experiments, with explosive liquids containing small bubbles of a gas to demonstrate extremely strong influence of the bubbles on the level of sensitivity of the liquids to impact.

During half of a century to proceed after these events theory of initiation at slow mechanical stimuli had developed preeminently along the ways marked by these discoveries. A group of scientists in the Institute of Chemical Physics, Moscow (A. Dubovik, A. Denisaev, et al.) elaborated the Bowden conception. American investigators (J. Starckenberg, M. Hershkovitz, et al.) developed essentially the problem of set back. The group of Prof. F. Bowden followers (J. Field, G. Cooley, et al.) performed the extensive investigations in the Laboratory of Surfaces. Cambridge University.

One of the peculiarities of experimental investigations in the field of initiation of explosives is the unusually strong scatter of the experimental results. Curve of frequency of explosions versus energy, pressure or velocity of impact usually intends to proceed with a very low tangent to the horizontal axis. Critical value of the influence sometimes seems to be estimated with a very low level of exactness.

To avoid this difficulty several series of experiments were performed in our Laboratory with different types of tools providing the special kind of impulsive coercion on a small sample of EM. Experiments were performed in collaboration with Yu.N. Polikarpov and, by the late, E.I. Dorofeev.

Ignition at quick compression of gas intrusions of a row of liquid EM was being investigated by means of application of the steel U-shaped tube one end of which was connected through the plastic disc with receiver containing compressed nitrogen. Another end of the tube was sealed. The explosive liquid was immersed in the lower section of the tube. When the plastic disc was ruptured the column of liquid in the tube is set to motion by the jet of nitrogen rushing into the tube and impinges upon the tube end. The procedure can be used to produce data that revealed the role of air inclusions in causing ignitions during the rapid compression of a liquid in the broad range of conditions of its production or transportation. The simple formula

$$P_{cr} = \left[ \left( \frac{x_0 P'_0}{u_0 \rho R T_b} \right)^{\frac{\gamma-1}{\gamma(v-n)+1}} - 1 \right] (\gamma - 1)^{-1}, \quad (1)$$

(Where  $P_{cr}$  is the critical pressure (critical driving force) necessary for initiation,  $P'_0$  is the arbitrary rate of the pressure drop,  $x_0$  is the original gap width,  $u_0$  and  $v$  are the constants of the Vielle law,  $\rho$  is the density of the liquid,  $R$  is the specific gas constant,  $T_b$  is the adiabatic temperature of burning,  $\gamma$  is adiabatic exponent and  $n$  is a constant reflecting dependence of  $P'_0$  on pressure in the gap) is proposed to calculate the critical driving force resulting in initiation of the liquid.

A set of 21 liquid high explosives investigated is divided in three groups. The first of them includes very sensitive explosives (NG, Methylnitrate, NGL, FEFO, ADN melt, etc.) subjected to initiation in the range of  $P_{cr}$  of 8 to 23 atm. Explosives of moderate sensitivity (TNT melt and DNT/Nitric Acid 70/30 solution) are initiated in the range of 60 to 80 atm. At last, the liquid explosives of the third group assumed to be insensitive liquids (NM, TNM, water-impregnated explosives), can not be ignited at the limit pressure of our installation, 100-150 atm.

The formula (1) gives a good fit to the experimental results only for the liquids of the first group. The second and the third groups representatives demonstrate  $P_{cr}$  data several times higher than the formula (1) to provide. It is disclosed in this presentation that the difference is stipulated by the fact that at very high final pressure in the gap the strong compression of the liquid and expansion of the tube take place followed by the loss of energy and corresponding  $P_{cr}$  enhancement. An expression of the form

$$\Delta P_{cr} = x P_f^2, \quad (2)$$

(Where  $\Delta P_{cr}$  is the difference in the driving force connected with the effects of compression and expansion,  $P_f$  is the final pressure in the gap and  $x$  is the function of compressibility of the liquid and geometry and mechanical characteristics of the tube) is proposed to explain the results of the majority of measurements.

Another procedure consists of employment of the fallhammer impact machine (up to 36 kg falling weight, 1.5 m height limit). The impact device contains a hole of the definite diameter and depth at the bottom of which the small portion of solid explosive is pressed. The plastic substance, ceresine (wax from ozocerite) flows into the hole under the falling weight impact, and compresses air inside the hole. The method reflects some of the conditions of ignition of explosive at in bore premature explosions. Six high explosives were investigated: TNT, TNT/RDX 40/60, Okfol (HMX + 3.5% phlegmatizer), Comp. 1 (RDX + 5-6% phlegmatizer), Comp. 2 (Comp.1 + 20% atomized aluminum) and Comp. 3 (RDX, TNT, Al and a phlegmatizer). In all cases the results of the experiments in  $\log p_m$  (maximal pressure of impact) vs.  $\log v_0$  (initial volume of the cavity) plane have a form of a cloud of «go» and «no-go» points strictly divided from the cloud of only «no-go» points with a straight line

$$\log p_m = m - n \log v_0, \quad (3)$$

where  $m$  and  $n$  are constants. In correspondence with a theoretical model  $n$  is close to 1/3 if a height of the hole were equal the hole diameter.

As a result the relation

$$Z = P V_0^n \quad (4)$$

where  $P = p_m/p_0$ ,  $V_0 = v_0/v_{00}$  and  $(p_0 \cdot v_{00}) = \text{Const.}$  (0.1 MPa and 1 mm<sup>3</sup>, corr.) was used to construct an «invariant of ignition probability» which does not depend on pressure of impact and a volume of cavity per se. This allows particularly to derive the density of ignitions probability  $\omega$  as a function of  $Z$  and to calculate the maximal permissible stress at a given volume of the cavity, or the maximal permissible volume at a given maximal stress, corresponding to probability of ignitions preeminently designated.

In the case of TNT and in some other cases, at more complicated conditions of the experiment, the numbers  $n$  and  $m$  may change steeply at the  $v_0$  enhancement. The model undergoes the definite alteration. However the critical character of the overall dependence, the sharp border between ignition and non ignition areas are preserved in all of the cases, and the method of calculation of the parameters of ignition would remain as before.

# About Combustion Phenomena of Double-Base Propellant Under Conventional- and Plasma-Ignition Conditions

*B. Baschung and D. Grune*

French-German Research Institute Saint-Louis, P.O. BOX 34, 68301 St-Louis Cedex, France

As it sometimes happens at real firings, the weapon destroys by faulty propellants or by unsatisfactory ignition. This last point is well known as *negative difference gas pressure* established by calculations of the interior ballistic cycles. These effects are disastrous as well as in rocket motors. Numerous experiments are performed to predict a faultness combustion of the used solid propellant so the risk of weapon destruction can be minimized.

This report describes some closed vessel methods to check a regular burning behavior or to interpret an irregular combustion. It is shown by experimental results that this irregular combustion is noticed by the followed circumstances:

1. Faulty manufacturing process: the propellant grains are broken in a very early phase of the combustion.
2. Incompatible components in the propellant mass: the burning becomes irregular and changes from burning to deflagration. Pressure rise and burning interruption explain this behavior.
3. Changing of the mechanical qualities: it is shown by burn rate measurements that the brittle point of JA2 is reached near  $-40^{\circ}\text{C}$ .
4. Incorrect ignition: as an example, results of a new ignition system (ETC) show the influence of the propellant position in the propellant bed on the combustion.

Micro-porosity by thermal defects is not considered here. But a new method is proposed to define a critical porosity of the propellant.

# Noise and Errors in Laser Recoil Measurements

*F. Cozzi and A. Balasini*

Dipartimento di Energetica, Politecnico di Milano, MI, Italy

*R. Hessler*

Consultant, Somerville, AL, USA

Laser recoil is a diagnostic technique, originally proposed in the United States (1972), to assess the combustion response of solid rocket propellants. This technique evaluates the response of the tested material to fluctuations of radiant heat flux by directly measuring the recoil force generated by the mass efflux from the burning surface. A CO<sub>2</sub> or Nd:YAG laser is the radiant source commonly used today. This approach allows several advantages with respect to standard techniques: measurement of the combustion response can be direct, both magnitude and phase can be measured, in principle no frequency limitation exists, many frequencies can be tested in just one experimental run, operations are fast and cheap, small size samples are needed. Thus, laser recoil is a promising technique. Nevertheless difficulties are also met. In particular, the small value of recoil thrust oscillations (few hundredth of grams) requires a very sensitive force transducer and great care in minimizing noise and errors sources. Acoustic pressure waves, mechanical vibrations, electric interferences, and background noise are able to deteriorate the quality of the measured signals, thus increasing data scatter and making interpretations of final results difficult. This is especially true for those materials showing a low response to heat flux, such as HMX, RDX and AP-based solid propellants when tested under a CO<sub>2</sub> laser. A comparison of measured CO<sub>2</sub> laser-driven combustion response for three different solid propellants is reported and noise effects are discussed. Some hints to reduce noise and errors are suggested, and results so far obtained are shown.

# **Sampling and Characterization of Condensed Combustion Products of Metalized Propellants. Problems and Perspectives**

*O.G. Glotov, V.E. Zarko, V.V. Karasev and A.D. Rychkov*

Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

Problems of representative sampling and subsequent characterization of the condensed combustion products are shown to connect closely with mechanism of formation of metal agglomerates, their structure and motion in two-phase flow, temporal evolution of size distribution, etc. Important feature of combustion process is its statistic and stochastic character that leads to formation of polydisperse size distribution of agglomerates with different internal structure. These issues should be taken into account in analysis and comparison of available experimental data. For illustration, experimental data are presented corresponding different propellant types.

To get reliable information about the combustion law of real agglomerates and to solve specific problems of data analysis and interpretation a novel experimental approach is discussed. The approach provides obtaining given size agglomerates burning in well characterized conditions. For this end special "super heterogeneous propellant" is designed and tested. The propellant consists of homogenized non-metalized matrix, which contains finite number of small volume inclusions of highly metalized energetic material simulated the content of "pockets" in real composite metalized propellants. In combustion of super heterogeneous propellant each inclusion generates agglomerate that burns in the flow of combustion products of non-metalized matrix.

Some calculation results are presented of two-dimensional two phase flow in actually used sampling bomb geometry along with first results of experimental study of burning and drag law for model agglomerates formed in combustion of super heterogeneous propellant.

# Numerical Modelling of Composite Propellant Combustion

*F. Miccio*

Istituto di Ricerche sulla Combustione - C.N.R., Napoli, Italy

An innovative 2D numerical model of composite propellant combustion is proposed. It takes into account the detailed description of the propellant topology, five chemical reactions, gas molecular diffusion and heat transfer in gas phase. Partial differential equations are numerically solved introducing a topological matrix. The propellant surface is determined by scanning the topological matrix and performing a series of logical tests. The bi-dimensional profiles of the temperature and molar fractions in the spatial domain are obtained. The average surface temperatures are also evaluated in both binder and oxidizer regions, as well as the linear burning rate. The model is able to predict the time evolution of the composite propellant after ignition. A non planar evolution of the propellant surface is predicted during combustion for different propellant topologies according with experimental observations of the propellant surface reported in literature. The propellant topology, the pressure, the oxidizer-binder mass ratio and the characteristic dimension play a large role on surface temperatures and linear burning rate. They increase with pressure and decreases, with asymptotic tendency, at increasing of both mass ratio and characteristic size. High burning rate are predicted for topologies which enhance the mixing between binder and oxidizer, in particular when fine spherical particles of the oxidizer are dispersed within a binder matrix.

**LIST OF WORKSHOP PARTECIPANTS WITH COMPLETE ADDRESSES**  
**Politecnico di Milano, Milano, Italy, 15-16 March 1999**

**Asa Lorenzo, Mr.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**Colombo Giovanni, Mr.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3871  
Fax No. (0039-02) 2399-3940  
E-mail colombo@clausius.energ.polimi.it

**Baschung B., Dr.**

ISL  
5 rue du Général-Cassagnou  
68680, Saint Louis  
France  
Telephone No. 0033-38969 5073  
Fax No. 0033-38969 5002  
E-mail

**Corsetti Elisabetta, Dr.**

FIAT-AVIO Comprensorio BPD  
Corso Garibaldi  
00034 Colferro, Roma  
Italy  
Telephone No. (0039-06) 9729-2518  
Fax No. (0039-06) 9729-2738

**Benzoni Giacomo, Mr.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**Cozzi Fabio, Dr.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3872  
Fax No. (0039-02) 2399-3940  
E-mail cozzi@clausius.energ.polimi.it

**Carretta Ubaldo, Dr.**

CNR-TEMPE  
via Cozzi, 53  
20125 Milano  
Italy  
Telephone No. (0039-02) 6617 3293  
Fax No. (0039-02) 6617 3294  
E-mail carretta@tempe.mi.cnr.it

**De Luca Luigi, Prof.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3912  
Fax No. (0039-02) 2399-3940  
E-mail deluca@icil64.cilea.it

**Cauty Franck, Dr.**

ONERA  
Chemin de la Hunière  
91761 Palaiseau Cedex, Palaiseau  
France  
Telephone No. 33 1 69 93 60 37  
Fax No. 33 1 69 93 61 62  
E-mail cauty@onera.fr

**Dondé Roberto, Dr.**

CNR-TEMPE  
via Cozzi, 53  
20125 Milano  
Italy  
Telephone No. (0039-02) 6617 3293  
Fax No. (0039-02)-66173294  
E-mail donde@tempe.mi.cnr.it

**LIST OF WORKSHOP PARTECIPANTS WITH COMPLETE ADDRESSES**  
**Politecnico di Milano, Milano, Italy, 15-16 March 1999**

**Galfetti Luciano, Prof.**

Dipartimento di Energetica  
 Politecnico di Milano  
 Piazza L. da Vinci, 32  
 20133 Milano  
 Italy  
 Telephone No. (0039-02) 2399-3926  
 Fax No. (0039-02) 2399-3940  
 E-mail galfetti@clausius.energ.polimi.it

**Grune Dietrich, Dr.**

ISL  
 5 rue du Général-Cassagnou  
 68680, Saint Louis Cedex  
 France  
 Telephone No. 0033-38969 5073  
 Fax No. 0033-38969 5002  
 E-mail

**Galli Claudio, Mr.**

Dipartimento di Energetica  
 Politecnico di Milano  
 Piazza L. da Vinci, 32  
 20133 Milano  
 Italy  
 Telephone No. (0039-02) 2399-3877  
 Fax No. (0039-02) 2399-3940  
 E-mail ltf@clausius.energ.polimi.it

**Guarnieri Claudio, Mr.**

CNR-TEMPE  
 via Cozzi, 53  
 20125 Milano  
 Italy  
 Telephone No. (0039-02) 6617 3340  
 Fax No. (0039-02) 6617 3294  
 E-mail guarnieri@tempe.mi.cnr.it

**Giambelli GianCarlo, Prof.**

Director Dipartimento di Energetica  
 Politecnico di Milano  
 Piazza L. da Vinci, 32  
 20133 Milano  
 Italy  
 Telephone No. (0039-02) 2399-3800  
 Fax No. (0039-02) 2399-3940  
 E-mail

**Harrison Letitia, Dr.**

US Office of Naval Research International Field  
 Office Europe  
 223-231 Old Marylebone Road  
 NW1 5TH London  
 England  
 Telephone No. +44-171-514-4922  
 Fax No. +44-171-723-6359  
 E-mail LHARRISON@ONREUR.NAVY.MIL

**Giuliani Piero, Dr.**

CNR-TEMPE  
 via Cozzi, 53  
 20125 Milano  
 Italy  
 Telephone No. (0039-02) 6617 3340  
 Fax No. (0039-02) 6617 3294  
 E-mail giuliani@tempe.mi.cnr.it

**Hessler Richard O., Mr.**

Consultant  
 93 Cryer Road  
 Somerville  
 AL 35670  
 USA  
 Telephone No. (256) 778-8014  
 Fax No.  
 E-mail ROHessler1@aol.com

**Glick Robert L., Dr.**

Consultant  
 1159S 525E  
 Rensselaer  
 IN 47978  
 USA  
 Telephone No. (219) 394-2872  
 E-mail marilynpg@liljasper.com

**Howland Jay A., Dr.**

European Office of Aerospace Research and  
 Development  
 223-231 Old Marylebone Road  
 NW1 5TH London  
 England  
 Telephone No. +44-171-514-4437  
 Fax No. +44-171-514-4960  
 E-mail jhowland@eoard.af.mil

**LIST OF WORKSHOP PARTECIPANTS WITH COMPLETE ADDRESSES**  
**Politecnico di Milano, Milano, Italy, 15-16 March 1999**

**Kondrikov Boris N., Prof.**  
Mendeleev University of Chemical Technology  
9 Miuskaya Sq.,  
125047, Moscow  
Russia  
Telephone No. (095) 496-9066  
Fax No. (095) 200-4204  
E-mail bkondr@orc.ru

**Novozhilov Boris V., Prof.**  
Semenov Institute of Chemical Physics,  
Russian Academy of Sciences  
4 Kosygina Street, 117977 Moscow V-334,  
Russia.  
Telephone No. (007-095) 939-  
Fax No. (007-095) 938-2156  
E-mail boris@center.chph.ras.ru

**Menalli Andrea, Mr.**  
Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3872  
Fax No. (0039-02) 2399-3940  
E-mail menalli@clausius.energ.polimi.it

**Palozzo Sarah, Ms.**  
Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**Miccio Francesco, Dr.**  
Istituto Ricerche Combustione - CNR  
via Metastasio 17  
Napoli  
Italy  
Telephone No. (0039-081) 593 5379  
Fax No. (0039-081) 593 1567  
E-mail miccio@irc.na.cnr.it

**Pein Roland, Dr.**  
Head Missile Propulsion Group  
DLR German Aerospace Center  
74239 Hardthausen  
Germany  
Telephone No. 0049 6298 28 324  
Fax No. 0049 6298 28324  
E-mail Roland.Pein@dlr.de

**Milazzo Michele, Mr.**  
Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**Ramaswami, Dr.**  
Dept. of EE  
University of Maryland  
MD 20742  
College Park  
USA  
Telephone No. (301) 4053 671  
Fax No. (301) 3149 281  
E-mail albalal@eng.umd.edu

**Morandi Christian, Mr.**  
Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail LTF@clausius.energ.polimi.it

**Rampichini Simone, Mr.**  
Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**LIST OF WORKSHOP PARTECIPANTS WITH COMPLETE ADDRESSES**  
**Politecnico di Milano, Milano, Italy, 15-16 March 1999**

**Restelli Monica, Ms.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**Verri Maurizio, Prof.**

Dipartimento di Matematica  
Politecnico di Milano  
Piazza L. da Vinci 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399 4526  
Fax No. (0039-02) 2399 4568  
E-mail mauver@mate.polimi.it

**Ruspa Denis, Mr.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**Zarko Vladimir E., Prof.**

Institute of Chemical Kinetics and Combustion  
Russian Academy of Sciences  
Institutskya, 3  
630090 Novosibirsk  
Russia  
Telephone No. (007-3832) 332 292  
Fax No. (007-3832) 342-350  
E-mail zarko@ns.kinetics.nsc.ru

**Russo Sorge AnnaMaria, Prof.**

Dipartimento di Ing. Aerospaziale  
Università di Napoli  
P.le Tecchio 80  
80125 Napoli  
Italy  
Telephone No. (0039-081) 7682 355  
Fax No. (0039-081) 5932 044  
E-mail russosor@unina.it

**Zenin Anatoli A., Prof.**

Semenov Institute of Chemical Physics  
Russian Academy of Sciences  
4 Kosygina Street  
117977 Moscow  
Russia  
Telephone No. (007-095) 939-7355 office  
Fax No. (007-095) 939-7417  
E-mail ZENIN@zenin.msk.ru

**Servieri Matteo, Mr.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

**Tussiwand Giuseppe, Mr.**

Dipartimento di Energetica  
Politecnico di Milano  
Piazza L. da Vinci, 32  
20133 Milano  
Italy  
Telephone No. (0039-02) 2399-3877  
Fax No. (0039-02) 2399-3940  
E-mail ltf@clausius.energ.polimi.it

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DIPARTIMENTO di ENERGETICA**

**International Workshop on  
Errors and Noise in  
Energetic Material Combustion Experiments**

15-16 Marzo 1999

We wish to thank the following for their contribution to the success of this conference:

- Politecnico di Milano (PoliMi, Milano, Italy);
- Ministero dell'Università e della Ricerca Scientifica e Tecnologica (MURST, Roma, Italy);
- Agenzia Spaziale Italiana (ASI, Roma, Italy);
- Landau Network Centro Volta (LNCV, Como, Italy);
- European Office of Aerospace Research and Development, Air Force Office of Scientific Research, United States Air Force Research Laboratory;
- United States Army Research Development and Standardization Group (UK), and
- United States Office of Naval Research, Europe.