EXTINGUISHMENT OF SOLID PROPELLANT FLAMES: A THEORY BASED ON A NEW FEEDBACK LAW

(Presentation Version)

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by

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Transmitted by

Martin Summerfield
Principal Investigator

This report is composed of reproductions of the slides presented at the Third ICRPG/AIAA Solid Propulsion Conference, Atlantic City, New Jersey, June 4-6, 1968. Additional copies of this presentation version are available from Princeton University.

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EXPLANATORY NOTE

Presentation Version

This report consists of reproductions of the slides comprising the presentation given at the Third ICRPG/AIAA Solid Propulsion Conference in Atlantic City, New Jersey on June 4-6, 1968. As such it does not include the verbal explanations that accompanied the slides. No manuscript was prepared for the Conference, but it is hoped that, despite its terseness, this document will serve as a useful summary of the material presented at the Conference. Work on this topic is still continuing and a later report will include revisions of these results along with new results.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title Page</td>
<td>i</td>
</tr>
<tr>
<td>Explanatory Note</td>
<td>ii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iii</td>
</tr>
<tr>
<td>Presentation Title Page</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>2</td>
</tr>
<tr>
<td>Experimental Results on Extinguishment</td>
<td>3</td>
</tr>
<tr>
<td>A. Typical Experimental Data</td>
<td>3</td>
</tr>
<tr>
<td>B. Composite of Experimental Data</td>
<td>4</td>
</tr>
<tr>
<td>Review of Previous Theoretical Works</td>
<td>5</td>
</tr>
<tr>
<td>Pressure-Frequency Regime of Interest</td>
<td>6</td>
</tr>
<tr>
<td>Theoretical Formulation</td>
<td>7</td>
</tr>
<tr>
<td>A. Coordinate System</td>
<td>7</td>
</tr>
<tr>
<td>B. Gas Phase Flame Equations</td>
<td>8</td>
</tr>
<tr>
<td>C. KTSS Integration of Gas Phase Flame Equations</td>
<td>9</td>
</tr>
<tr>
<td>D. Solid Phase Equation and Boundary Conditions</td>
<td>10</td>
</tr>
<tr>
<td>Theoretical Predictions</td>
<td>11</td>
</tr>
<tr>
<td>A. Pressure Decay Used in Theoretical Analysis</td>
<td>11</td>
</tr>
<tr>
<td>B. Predicted Flame Temperature During Depressurization</td>
<td>12</td>
</tr>
<tr>
<td>C. Experimental Curve of Luminosity During Depressurization (from Ciepluch)</td>
<td>13</td>
</tr>
<tr>
<td>D. Surface Temperature and Burning Rate During Depressurization</td>
<td>14</td>
</tr>
<tr>
<td>E. Extinction Map</td>
<td>15</td>
</tr>
<tr>
<td>Comparison of Theory With Experiment</td>
<td>16</td>
</tr>
<tr>
<td>A. Comparison of Several Theories With Ciepluch Data</td>
<td>16</td>
</tr>
<tr>
<td>B. Effect of O/F Ratio on Extinction</td>
<td>17</td>
</tr>
<tr>
<td>Effect of Aluminum Addition</td>
<td>18</td>
</tr>
<tr>
<td>A. Effect of Aluminum on Transient Flame Temperature</td>
<td>18</td>
</tr>
<tr>
<td>B. Effect of Aluminum on Transient Burning Rate and Surface Temperature</td>
<td>19</td>
</tr>
<tr>
<td>C. Comparison of Theory and Experiment</td>
<td>20</td>
</tr>
<tr>
<td>Conclusions</td>
<td>21</td>
</tr>
</tbody>
</table>

iii
EXTINGUISHMENT OF SOLID PROPELLANT FLAMES:
A THEORY BASED ON A NEW FEEDBACK LAW

by

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Sponsored by ONR Contract Nonr 1858(32)

Supervised by the Power Branch
of the Office of Naval Research
This paper includes:

1. A critical examination of previous theories of extinguishment and reasons for a new approach.


3. Predictions of the time variation of burning rate, surface temperature, and flame temperature during rapid depressurization:
   a) Extinguishment case.
   b) Non-extinguishment case.

4. Predictions of the effects of oxidizer loading and aluminum content on the difficulty of extinguishment.

5. Comparison of the predictions with experimental results of Ciepluch and others.
DIFFICULTY OF EXTINCTION BY DEPRESSURIZATION: EXPERIMENTAL DATA
DIFFICULTY OF EXTINCTION BY DEPRESSURIZATION
COMPOSITE OF EXPERIMENTAL DATA
## Previous theories of extinguishment:

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Institution</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Von Elbe</td>
<td>ARC</td>
<td>1963, 1966</td>
</tr>
<tr>
<td>Paul</td>
<td>Aerojet</td>
<td>1964</td>
</tr>
<tr>
<td>N. Ryan, Donaldson, Baer, P. Ryan and Mantyla</td>
<td>Utah</td>
<td>1966, 1967</td>
</tr>
</tbody>
</table>
PRESSURE-FREQUENCY REGIMES OF ACOUSTIC INTERACTION WITH COMBUSTION ZONE

HIGH FREQUENCY REGION
(LAG IS IN GAS FLAME AS WELL AS SOLID)

HIGH PRESSURE REGION
(NO TESTED FLAME MODEL EXISTS)

LOW FREQUENCY REGION
(LAG IS IN SOLID HEAT-UP ZONE, NOT GAS FLAME)

ZERO FREQUENCY REGION
(NO LAG ANYWHERE IN COMBUSTION ZONE)

\[ \frac{1}{10} \tau_{\text{GAS REACTION TIME}} \]

\[ \frac{1}{10} \tau_{\text{SOLID HEAT-UP TIME}} \]
KTSS MODEL FOR
NONSTEADY SOLID PROPELLANT BURNING

HEAT RELEASE PARAMETER

\[ H = \frac{Q_s}{c_s(T_{so} - T_\infty)} \]
ENERGY EQUATION FOR GAS PHASE

\[ \lambda g \frac{d^2T}{dx^2} + r \rho c \frac{dT}{dx} + \rho g Q_f \dot{e} = 0 \]

\[ -\lambda_s \left( \frac{\partial T}{\partial x} \right)_s = \frac{\Phi(p)}{r} \left[ 1 - \exp\left\{ -\rho_p r^2 Q_f / \phi(p) \right\} \right] \]

\[ \phi(p) = \frac{\lambda g Q_f \rho}{\rho_p c \tilde{T}_c} \]
EVALUATION OF $\phi(p)$ AT STEADY STATE

$$q_g = \frac{\phi(p)}{r}[1 - \exp - \rho_p(r)^2 q_e/\phi(p)]$$

$$q_g = \rho_p \bar{r}[c(T_s - T_\infty) - Q_s]$$

$$\bar{r} = ap^n$$

$$\phi(p) = \frac{\rho_p(ap^n)^2[c(T_s - T_\infty) - Q_s]}{[1 - \exp\{-\rho_p(ap^n)^2 q_e/\phi(p)\}]}$$
ENERGY EQUATION FOR SOLID PHASE

\[ \frac{\partial T}{\partial t} = r(t) \frac{\partial T}{\partial x} + \alpha \frac{\partial^2 T}{\partial x^2} \]

where \( r(t) = A \exp(-E_s/RT_s) \)

B. C.

\[ -\lambda_p \left( \frac{\partial T}{\partial x} \right) = q_g + r \rho \rho Q_s \]

\[ T(\infty) = T_\infty \]

\[ T(x,0) = (T_{s,0} - T_\infty) \exp(-x\rho_0/\alpha) \]
\[ P = p_o - (p_o - p_f) \left[ 1 - e^{-\beta \tau} \right] \]
\[ \beta = -\left( \frac{dp}{dt} \right)_0 \left[ \left( \frac{\alpha p}{r_o^2} \right) / (p_o - p_f) \right] \]

\[ P = P/p_o \]

**Exponential Pressure Decay**

*Used in Depressurization Analysis*
\[ \Theta_f = \frac{T_f - 300}{900 - 300} \]

\[ \gamma = \frac{t}{\alpha e^{r_0^2}} \]

**Propellant:**
\[ E_s = 16 \text{ Kcal/mol} \]
\[ H = 0.7 \]

**Note:** For visual comparison the time scale of the \( \beta = 0.11 \) case was expanded in this plot in order to make the two curves coincide at start.

**Predicted History of Flame Temperature During Rapid Depressurization**
Typical luminosity and chamber pressure transient records during rapid pressure decay

Taken from Ciepluch, ARS J., Nov. 1961 (His Figure 2)
Predicted history of surface temperature and burning rate during rapid depressurization.

**Propellant:**
- $E_s = 16$ kcal/mol.
- $H = 0.7$

**Failed to extinguish:**
- $\beta = 0.08$

**Beta = 0.11 extinguished**

**Note:** For visual comparison, the time scale of the $\beta = 0.11$ case was expanded in this plot in order to make the two curves coincide at the start.
DIFFICULTY OF EXTINCTION BY DEPRESSURIZATION: EFFECT OF PRESSURE DROP
DIFFICULTY OF EXTINCTION BY DEPRESSURIZATION: COMPARISON OF THEORY AND EXPERIMENT
DIFFICULTY OF EXTINCTION BY DEPRESSURIZATION

EFFECT OF AP LOADING (O/F) RATIO
\[ \Theta_f = \frac{T_f - 300}{900 - 300} \]

**Propellant:**
- \( E_s = 16 \text{ kcal/mol} \)
- \( H = 0.7 \)

**Depressurization:**
- \( \beta = 0.17 \)
- \( \Delta P = 95\% \)

- \( \Theta_f \) (Steady State)
- \( \Theta_f \) (Aluminized)
- \( \Theta_f \) (Non-Aluminized)
- \( \Theta_f \) (Isentropic Postulate)

**Predicted History of Flame Temperature During Rapid Depressurization to Extinguishment**

\( \tau \) is the non-dimensional time.
Predicted history of surface temperature and burning rate during rapid depressurization to extinguishment.

Propellant:
- $E_s = 16 \text{ kcal/mol}$
- $H = 0.7$
- $T_{i0n} = 600^\circ$K

Depressurization:
- $\beta = 0.17$
- $\Delta P = 95\%$

Combustion assumed to stop at $T_s = 600^\circ$K.

At higher temperatures: $R \sim \exp(-E_s/R_{T_s})$
DIFFICULTY OF EXTINCTION BY DEPRESSURIZATION:
EFFECT OF ADDITION OF ALUMINUM

ALUMINIZED LINE ESTIMATED FROM EXPERIMENTAL DATA OF CIEPLUCH

- 73.5% AP
- 17.5% FUEL
- 9.0% AL

CIEPLUCH EXPERIMENTAL DATA

- 81% AP
- 19% FUEL

NON-ALUMINIZED

M/S THEORY BASED ON KTS MODEL, H = .7

NON-ALUMINIZED

CRITICAL INITIAL DEPRESSURIZATION RATE

\( \frac{dp}{dt} \) (psi/sec. x 10^-3)

INITIAL CHAMBER PRESSURE (psia)
In conclusion we have shown that:

1. A theory based on the KTSS dynamic flame model (surface heat release plus granular diffusion flame) predicts qualitatively the observed extinguishment behavior.

2. An aluminized propellant is more difficult to extinguish than a non-aluminized one having the same AP binder ratio.

3. The low pressure part of the depressurization transient is the most critical in determining whether extinction will occur.

4. To improve the predictions, the theory will have to incorporate a more exact description of the entire burning rate curve.