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DEPARTMENT OF CHEMICAL ENGINEERING

EXTINCTION OF BURNING SOLID PROPELLANT

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Brigham Young University
Department of Chemical Engineering

Final Report

Extinction of Burning Solid Propellant

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INTRODUCTION

At the beginning of this program, an evaluation of the literature in the solid propellant extinction field showed that there was a considerable amount of good experimental data available (1,2,3). Although some theoretical work had also been done (4), it was felt that the initial efforts would be most profitably directed toward improving the status of the theory. Accordingly the program was set up to first, develop an improved theoretical model; second to compare the model with existing experimental data; third, to gether any additional experimental data necessary and fourth, to expand either the experimental or theoretical program as the results indicated.

THEORY

The theoretical effort was based on the premise that the results ought to be useful to the design engineer and to be useful, the theory must not be too complex or sophisticated. At least, this seems to be true in the closely related field of combustion instability where a sizeable output of complex theory has had practically no impact on the design field. Therefore, a simple thermal model was chosen to represent the combustion process. This thermal model was indicated first because the Von Elbe treatment agreed with experiment in many cases and second, because the characteristic heat up time of the solid propellant seemed to be the only characteristic time of the combustion process which had the same magnitude as the extinction time for the propellant.

Accordingly, the combustion process was pictures as follows. The homogeneous, one-dimensional solid propellant with constant thermal properties is heated to a critical pressure-independent surface temperature where it sublimes and then reacts in the gaseous phase. The gas phase processes are comparatively rapid and for pressure transients just fast enough to extinguish the combustion, the gas behavior is dependent only on the instantaneous pressure. Extinction occurs when the transient pressure causes the propellant surface temperature to drop below the critical value.

Appendix 1, which is a copy of a paper presented at the June, 1967 ICRPG/AIAA Solid Propulsion Symposium in Anaheim, California, presents a detailed development of the theory. This appendix also presents the theoretical results in some detail.

Where possible, the theoretical predictions were compared with the experimental data available in the literature. Qualitative agreement was realized from a qualitative comparison. However, quantitative comparison could not be made because the data in the literature were not presented in sufficient detail.

EXPERIMENT

To remedy this deficiency, the requisite extinction data were gathered experimentally. The combustion chamber was patterned after that of Ciepluch (1) and the method of initiating the pressure transient was patterned after that used at the University of Utah (5). Thus the propellant would be ignited in a small rocket motor, the motor would reach design pressure, and then a pressure transient would be induced by rupturing a frangible diaphragm which sealed an auxiliary nozzle.

Both the experimental procedure and results are described in greater detail in Appendix 1 and Table 1 which present the results obtained from the testing of seven propellant variations. For the sake of simplicity, the table is based on the approximation that the pressure transients are exponential.

COMPARISON OF THEORY AND EXPERIMENT

As can be seen from Table 1, the theory developed in this program agrees with experiment better than the earlier work. This improvement is accompanied however, by increased difficulty of application. Also, even with this improvement, the theory is not yet adequate for design pruposes. No comparison was made between this theory and the more sophisticated theories now in existence because the more sophisticated theories cannot yet be quantitatively related to the experimental data.

ACKNOWLEDGEMENT

Special acknowledgement must be made to the personnel of the University of Utah and Hercules Inc. whose cooperation has eliminated duplication of effort and greatly assisted this work.

REFERENCES

1. Ciepluch, C.C., "Effect of Rapid Pressure Decay on Solid Propellant Combustion." ARS Journal Vol. 31, Page 1584, 1961.
2. Ciepluch, C.C., "Effect of Composition on Combustion of Solid Propellants During a Rapid Pressure Decrease." NASA Technical Note D-1559, 1962.
3. Ciepluch, C.C., "Spontaneous Reignition of Previously Extinguished Solid Propellants," NASA Technical Note D-2167, 1964.
4. Von Elbe, G., "Theory of Solid Propellant Ignition and Response to Pressure Transients." Interagency Solid Propulsion Meeting 3:96, 1963.
5. Donaldson, A.B., "Flame Extinction of Solid Propellants," Unpublished Masters Thesis, University of Utah, June, 1965.

TABLE I

Comparison of Theory and Experiment

Propellant*	Initial pressure (psia)	Experimental half time** (sec)	Reference 4 Theoretical half time (sec)	This Theory half time (sec)
A-13	165	.0100-.0107	.0040	.010-.0107
A-13	410	.006-009	.0016	.006-.009
A-13	90	.0105-.012	.0074	.0105-.012
A-14	280	.0056-.0085	.00064	.0028-.0043
A-14	155	.0057-.0085	.0017	.0043-.0058
A-16	320	.0016-.0022	.00019	.0008-.0011
A-15	285	.0053-.0075	.00093	.001-.0015
A-17	170	.0067-.0079	.046	.035-.04
A-18	155	.0062-.0070	.028	.031-.035
G	125	.0068-.0085	.0035	.0023-.0041

* See appendix 1 for compositions

** All of these runs were made to a final pressure of 12.5 psia. The interval represents the area separating a non-extinguishing run from one which extinguished.

APPENDIX 1

DEPRESSURIZATION INDUCED EXTINCTION BY BURNING SOLID PROPELLANT[1]

by

M.D. Horton[2], P.S. Bruno[3], E.C. Graesser[4]

ABSTRACT

This paper presents the results of a combined theoretical and experimental study of the process in which solid propellant combustion is terminated by a rapid drop in pressure. Experimentally, propellant burning in a small rocket motor was subjected to a rapid pressure drop when an auxiliary nozzle was suddenly opened. Such tests were run with varying nozzle sizes for the auxiliary nozzle and the boundary between extinction and non-extinction was determined. The results were then compared to the predictions of the theoretical model which was based on the assumption that extinction occurs when the heat absorption by the solid propellant exceeds the heat transfer to the solid propellant from the combustion gas. In general, the theoretical predictions agreed well with both the experimental results gathered in this program and those published by other investigators.

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INTRODUCTION

Many solid propellant applications are dependent upon the designer's ability to cause a termination of the propellant combustion. For example, a stop-start capability may be desired for space missions, and a termination is programmed for the last stage of a ballistic missile. Because of these needs, engineers have developed and used non-optimal termination techniques. Subsequent work in the area has been directed toward understanding extinction and improving this portion of a rocket's performance.

The experimental study of propellant extinguishment by pressure decreases has been performed largely in two types of apparatus. In one, the rarifaction tube, a pressure transient is produced by bursting a diaphragm at the end of a tube which contains a burning strand of propellant. The resultant pressure wave then impinges upon the propellant whose response to the transient is observed. The other technique involves firing a small motor, allowing it to reach operating pressure, and then stepwise increasing the nozzle area to cause a pressure transient.

Price(1) and McCune(2) reported early exploratory tests performed with rarifaction tubes. However, Mitchell(3) later showed that such extinction as was previously observed had probably been caused by the flow of cold, inert gas around the propellant strand. Donaldson(4) later performed an extensive series of rarifaction tube tests and obtained good qualitative results.

Ciepluch(5,6,7) studied the extinction of several propellants by the use of a small motor having an auxiliary nozzle which opened after steady state combustion was attained. The reports of his work describe the effect of propellant composition on reignition, and also the depressurization rate required to produce extinction. Reference 8 also describes results of this nature.

The theoretical studies performed thus far have been only partly successful. References 8 and 9 develop the transient burning rate equation:

$$\frac{r}{r_o} = 1 + \frac{\alpha n N}{b^2 P^{2n+1}} \frac{dP}{dt} \qquad (1)$$

which says extinction occurs (r = 0) when

$$\frac{-dP}{dt} = \frac{b^2 P^{2n+1}}{N \alpha n} \qquad (2)$$

According to Reference 8, N has a value of one or less, while Reference 9 says N has a value of 2.

Equation 2 provides a qualitative correlation of the experimental data, but a better theoretical description is required for two reasons. One reason is that, as Figure 1 show, the correlation is not adequate for general engineering use. Another reason is that Equation 2 does not consider the effect of total pressure drop which experiment(7) has shown to be important.

The object of this paper is to present the results of a study in which an improved theoretical model explaining extinction was developed. Also presented are experimental extinction data for propellant compositions not previously tested.

EXTINCTION MODEL

To derive a rigorous theory describing extinction, one would develop the time dependent heat conduction, diffusion, and kinetic equations for both the gas and solid phases of the combustion zone, and then solve them simultaneously. Besides being extremely difficult, this task would, upon completion, yield a very complex solution. In fact, the solution would be so complex and contain so many parameters whose values were unknown that such a solution would have little practical value.

The task could, perhaps, be simplified by the use of perturbational analysis, except that here again difficulties intervene. During the pressure transient being considered, many pertinent variables change by a factor of ten or greater. This being so, one must be concerned not with a perturbation of the initial conditions, but rather with the entire transient of interest.

Fortunately, the problem can be somewhat simplified if consideration is given to the various characteristic times for the combustion process. Reference 10 has shown that the characteristic times for the gaseous portion of the combustion zone are considerably smaller than the characteristic time associated with heat conduction in the solid propellant. Accordingly, the heat-up of the solid propellant is the slowest in the series of events that transforms the solid propellant into a hot combustion gas. Because the heating of the solid is the rate limiting (i.e. slowest) step, the minimum pressure transient which will terminate combustion is the one which is just fast enough to arrest this rate-limiting step.

In order to derive a thermal extinction criterion, it is first convenient to describe the steady state thermal profile in the solid propellant. The heat conduction equation in the solid propellant is:

$$\alpha \frac{\partial^2 T}{\partial x^2} - r_i \frac{\partial T}{\partial x} = \frac{\partial T}{\partial t} \qquad (3)$$

if it is assumed that:

(1) the heat conduction is one-dimensional

(2) there are no reactions beneath the propellant surface

(3) the thermal properties of the propellant are constant

(4) the propellant is homogenous and semi-infinite, and

(5) the coordinate system is fixed with respect to the propellant surface

At steady state $\frac{\partial T}{\partial t} = 0$ and the temperature distribution in the solid propellant is (see Figure 2):

$$\frac{T - T_o}{T_s - T_o} \quad \exp\left(\frac{rx}{\alpha}\right) \tag{4}$$

Now, it is further assumed that the propellant sublimes with a pressure-independent heat of sublimation when it is heated to a certain critical, pressure-independent temperature (T_s). Certainly, this is not an exact description of the surface decomposition, but it may be an adequate representation as will be determined by a comparison of the theoretical predictions and experimental data.

The consequence of these assumptions is that any time the surface temperature drops below T_s, extinction has occurred. Furthermore, the only way the surface temperature can drop is the for the heat conduction into the propellant to be greater than the heat conduction from the gaseous flame to the propellant surface.

The heat conduction into the solid is $k \frac{\partial T}{\partial x}\Big|_{x=0}$, whereas it is more difficult to describe the conduction to the surface. To facilitate this description, another approximation is made. This approximation is that the rate of heat conduction from the gas flame to the solid surface is characterized only by the pressure. That is, at a given pressure, the heat transfer is the same during a pressure transient as it would be if the pressure were constant. To some degree, the approximation is justified because the characteristic times for the gas are small compared with the characteristic time of the solid.(10) This means that the gas flame responds rapidly enough that its behavior is not time-dependent, but only pressure dependent. Again, the ultimate justification must come from satisfactory agreement between experiment and theory. The heat conducted into the solid from the surface is equal to that conducted to the surface minus the heat required to vaporize the solid. With the above assumptions and approximations, these respective terms are $k \frac{\partial T}{\partial x}\Big|_{x=0}$, $r\rho\lambda + r\rho c\,(T_s - T_o)$, and $r_i\rho\lambda$. The equation which relates these terms is:

$$k\frac{\partial T}{\partial x}\Big|_{x=0} = \rho\lambda\,(r - r_i) + r\rho c\,(T_s - T_o) \tag{5}$$

At this point Equation 3 describes the heat transfer in the solid, Equation 4 is a boundary condition describing the initial temperature profile when the pressure transient is induced, and Equation 5 describes the transient heat transfer to the solid surface. Additional boundary conditions are that T_s is a constant and the temperature at minus infinity is T_o.

For the sake of generality, these equations were non-dimensionalized by the use of the following definitions, many of which were used in Reference 8:

$$\theta = \frac{T - T_o}{T_s - T_o} \tag{6}$$

$$Y = \frac{r_o x}{\alpha}$$

$$\tau = \frac{r_o^2 t}{\alpha}$$

$$R = \frac{r}{r_o}$$

$$R_i = \frac{r_i}{r_o}$$

$$F = \frac{\lambda}{c(T_s - T_o)}$$

The substitution of these dimensionless variables converted the heat-transfer equations and boundary conditions to:

$$\frac{\partial^2}{\partial Y^2} - R_i \frac{\partial \theta}{\partial Y} = \frac{\partial \theta}{\partial \tau}$$

$$\left.\frac{\partial \theta}{\partial Y}\right|_{Y = 0} = (1 + F)\,R - R_i F \qquad (7)$$

$$\theta = 0 \text{ at } Y = -\infty$$

$$\theta = \exp Y \text{ at } \tau = 0$$

and $$\theta = 1 \text{ at } Y = 0$$

Provided that the relationship between R and τ(P and t) were known, one could, in principle, find an exact solution to this set of equations. However, even with a simple specification of R versus τ , the authors could not find an exact solution and resorted to numerical techniques. By the application of the backward method of differences, a tridiagonal system of difference equations was developed and then numerically solved with an IBM 7040 computer for two types of R vs. τ relationships.

The first type was chosen because it was a fair approximation of the relationship encountered experimentally. This form was based on the assumption that the pressure decay in the combustion system was described by the exponential equation:

$$\frac{P - P_a}{P_o - P_a} = \exp\left(\frac{-0.693\tau}{\tau_{1/2}}\right) \qquad (8)$$

while the steady state burning rate of the propellant could be described as:

$$r = bP^n \qquad (9)$$

Then, the equation

$$R = \frac{r}{r_o} = \left(\frac{P}{P_o}\right)^n \qquad (10)$$

was used along with Equations 8 and 10 to obtain

$$R = \left[\left(1 - \frac{P_a}{P_o}\right) \exp\left(\frac{-0.693}{\tau_{\frac{1}{2}}} \right) + \frac{P_a}{P_o} \right]^n \qquad (11)$$

Equations 7 and 11 were then solved numerically for the critical values of $\tau_{\frac{1}{2}}$ which represented the boundary condition between fast decays (small $\tau_{\frac{1}{2}}$) which theoretically caused extinction ($R_1 = 0$) and slower decays which did not. Figures 3 and 4 summarize the results.

In many cases of interest, either or both of Equations 8 and 9 did not adequately describe the transient. When this was so, Equation 11 was not used as a boundary condition but instead, the computer program used a data table of R versus τ as prepared from the strand burning rate curve and the pressure decay record of a particular extinction test. The numerical solution would then determine whether or not the propellant should have extinguished theoretically. The results of such tests were examined by this procedure and are presented later in the paper.

EXTINCTION TESTS

Although much experimental extinction data were available in the literature, they did not meet the needs of this program for two reasons. First, because propellant compositions not previously tested were of interest and second, because the data as presented did not allow a comparison between experiment and theory. That is, the pressure transients in the literature were non-exponential, so Equation 11 was not a valid boundary condition. Also, the experimental decays were rarely presented in a sufficient detail to permit the determination and use of a tabular boundary condition. One experimenter was generous enough to furnish the authors with his detailed experimental results.(11) However, the data were originally taken for different purposes and were not detailed enough to allow a direct comparison with theory.

Therefore, the propellant compositions listed in Table I were tested to determine the conditions required to extinguish the propellant combustion. This testing was done in motors which were ignited, allowed to come to operating pressure, and then subjected to a pressure transient by instantly opening an auxiliary nozzle. The use of several different auxiliary nozzle sizes established the boundary between the transient which extinguished combustion and the transient which did not. Studied in the program were the effect of propellant location, propellant composition, initial pressure, and final pressure. Table 2 presents a summary of the test results.

As Reference 6 has shown, small changes in composition can cause large changes in the extinguishment characteristics of a propellant. Other variables had less effect but were still significant.

DETERMINATION OF F

The reader may have noticed that all but one of the parameters used in the theory can be readily determined from routine laboratory tests. Recent work (12) has also made it possible to determine the value of F. Briefly, the value of F is determined as follows. A rarifaction tube is used to determine the total pressure drop required to extinguish a burning propellant strand as a function of depressurization rate. This curve is then extrapolated beyond the experimental limit to fine the required pressure drop (P_o to P_f) for an instantaneous drop in pressure. This parameter is then related to F by noting that, according to the assumptions made earlier, an instantaneous pressure drop will cause the heat flux from the gas phase to instantaneously readjust while the thermal profile in the solid is unchanged. The extinction condition is represented by the point where the heat conduction to the surface $r\rho\lambda + r\rho c \ (T_s - T_c)$ is just equal to the conduction away from the surface $r_o \rho c \, (T_s - T_o)$ and

$$r\rho\,[\,\lambda + c\,(T_x - T_o)\,] = r_o \rho c\,(T_s - T_o) \qquad (12)$$

Equation 9 is then used as

$$r = bP_f^{\,n} \qquad (13)$$

and

$$r_o = bP_o^{\,n}$$

then combined with Equation 12 to give:

$$\left(\frac{P_o}{P_f}\right)^n = \left[\frac{\lambda}{c\,(T_s - T_o)} + 1\right] \qquad (14)$$

which, after the substitution of F and rearrangement, becomes

$$F = \left(\frac{P_o}{P_f}\right)^n - 1 \qquad (15)$$

For several of the propellants tested in the extinction program, the values of F and the parameters used in their calculation are shown in Table III.

COMPARISON OF THEORY AND EXPERIMENT

Even though the theoretical model could not quantitatively be compared with the experimental data available in the literature, some qualitative comparisons were made. Ciepluch (Figure 3 in Reference 6) shows a graph of the maximum "half-decay time" ($t_{½}$), which will cause extinction as a function of initial pressure. From the definition of τ, we find that

$$\tau_{½} = \frac{r_o^{\,2}}{\alpha}\,t_{½} \qquad (16)$$

Now, to compare theory and experiment, the rather poor assumption was made that the experimental pressure decay is exponential. Then, for reasonable values of F (see Tables 2 and 4), Figures 3 and 4 show that $\tau_{½}$ is a constant over the pressure range being considered ($n = .34$, $P_a/P_o = .001$). As figure 5 shows, the experimental data have about the same values as the theory

(F = 0.1), but the experimental data show a slight slope. Accordingly, the model and experimental data show qualitative agreement which is about all that could be expected in this case.

Reference 6 presents data for the critical half decay time as a function of ambient pressure for an aluminized propellant. Figure 6 shows a comparison between the theory and the experimental results and again qualitative agreement is observed.

In one case, an illustration in the literature(5) presented exact pressure-time history during an extinction test. This history was used to prepare a table of R vs. τ for computer input. Then, with an assumed representative value of F = 0.10, the theory correctly predicted extinction. Because an exact value of F was unknown, this result represents qualitative agreement between experiment and theory.

Similarly, the F values for several of the propellants tested in this program were unknown. However, the use of an assumed value (0.14) and tabular input of the boundary condition yielded excellent agreement between the experimental results and the theoretical predictions with agreement being obtained in fourteen out of fifteen comparisons. This again constitutes good qualitative agreement.

For those propellants whose F values were known (See Table III), use of tabular input of the boundary condition provided a severe test for the theoretical model. These seven propellant compositions were tested and the theory correctly predicted extinction for 18 out of 25 tests. To determine how serious the error in the model was, the seven tests showing disagreement were further examined. Faster or slower decays were synthetically generated and used to determine the extinction-non-extinction boundary. By this process it was found that to predict extinction the model required depressurization rates which were in error by as much as a factor of five. For example, to predict extinction for run 119, the model needed a depressurization rate at least three times as fast as the experimentally observed value.

It is appropriate that this theory be compared with that presented in References 8 and 9. The perturbational approach used in those references yields a criterion which is very simple to use and which disagreed by no more than a factor of ten with the experimental results determined in this program. However, that approach wrongly predicts no relation between extinction and ambient pressure. The model presented in this paper requires complex numerical calculation but seems to be correct within a factor of five and correctly predicts trends. It would seem then, that the older theory is not as good but is easier to use.

One factor which was examined experimentally was the effect of propellant orientation in the combustion chamber. It was found that an end burner was slightly easier (25 percent smaller depressurization rate) to extinguish than a single slab subjected to parallel flow which in turn was slightly easier (20 percent) to extinguish than opposed slabs subjected to parallel flow.

The practical implications of Figures 3 and 4 are many. According to the theory, anything that lowers the effective propellant surface temperature or raises its "heat of sublimation" will make the propellant easier to extinguish. For low values of P_a / P_o, a small increase in either chamber pressure or pressure exponent can make a motor much easier to extinguish. Also, under any conditions, very low exponent propellants are difficult to extinguish. Unfortunately, the experimental data required to test these predictions are not available.

As the model was used, it was necessary to know the experimental pressure decay to see if the theory would predict extinction. The theory would be much more useful if it were coupled to a mass balance on the combustion chamber so that the computer would generate the pressure transient equation. While such a coupling was accomplished in this program, an overly simple mass balance was used and high quality results were not obtained.

DISCUSSION

At this point, consider how good the theory could be expected to be and then how good it actually is. The theoretical model is relatively simple and unsophisticated. The solid is not homogeneous, the thermal properties are not constant, the surface temperature is not constant, subsurface reactions almost surely occur, the use of the term λ represents a drastic simplification of the surface decomposition, and the representation of the gas phase heat transfer may be a poor approximation. With these objections in mind, one would not expect more than qualitative agreement between theory and experiment.

Now, the comparisons made showed qualitative agreement in all cases and quantitative agreement in most cases. This is better than one would expect, considering the simplicity of the theory and the wide range or propellant compositions considered. The theory then, consists of a fairly accurate thermal representation of the extinction process. Because all of the parameters used can be determined experimentally, no "guess" factors are left as uncertainties. Accordingly, the theory and experimental method ought to be useful to anyone concerned with practical extinction problems.

NOMENCLATURE

A	Exponential pressure decay exponent
b	Constant in Vielle steady state burning rate equation
c	Propellant heat capacity
F	Ratio of propellant heat of vaporization to heat required to raise propellant to surface temperature
k	Propellant thermal conductivity
n	Pressure exponent in Vielle burning rate equation
N	Coefficient in Von Elbe and Aerojet Extinction Theory
P	Instantaneous chamber pressure
P_a	Ambient pressure
P_f	Final pressure in rarifaction tube
P_o	Initial steady state chamber pressure
r	Steady state burning rate corresponding to P
r_i	Transient burning rate
r_o	Steady state burning rate corresponding to P_o
R	Dimensionless steady state burning rate $(\frac{r}{r_o})$
R_i	Dimensionless transient burning rate $(\frac{r_i}{r_o})$
t	Time
$t_{½}$	Largest time in which chamber pressure could decrease by 50% and still extinguish propellant
T	Temperature of propellant
T_o	Initial propellant temperature
T_s	Surface temperature of burning propellant
x	Distance from propellant surface

Y	Dimensionless distance $(r_o x/\alpha)$
α	Propellant thermal diffusivity
λ	Propellant heat of sublimation
ρ	Propellant density
Θ	Dimensionless temperature $\left(\frac{T - T}{T_s - T_o}\right)$
τ	Dimensionless time $(r_o^2 t/\alpha)$
$\tau_{1/2}$	Dimensionless half decay time $\left(\frac{r_o^2 t_{1/2}}{\alpha}\right)$

REFERENCES

1. Price, E.W., "Review of Experimental Research on Combustion Instability of Solid Propellants," in Progress in Astronautics and Rocketry - Vol. 1 (Academic Press, New York, 1960) pp. 561-602.

2. McCune, C.C., "Solid Propellant Ignition Studies in a Shock Tube," Un-published PhD Thesis, University of Utah (1961).

3. Mitchell, R.C., "Flame Spread on Solid Propellant," Unpublished PhD Thesis, University of Utah (1963).

4. Donaldson, A.B., "Flame Spread on Solid Propellant," Unpublished Masters Thesis, University of Utah (1965).

5. Ciepluch, C.C., "Effect of Rapid Pressure Decay on Solid Propellant Combustion," ARS J31, 1584 (1961).

6. Ciepluch, C.C., "Effect of Composition on Combustion of Solid Propellants Using a Rapid Pressure Decrease," NASA Technical Note D-1559 (1962).

7. Ciepluch, C.C., "Spontaneous Reignition of Previously Extinguished Solid Propellants," NASA Technical Note D-2167 (1964).

8. Paul, B.E., et.al., "A Ballistic Explanation of the Ignition Pressure Peak," AIAA Preprint 64-121 (1964). Also various Aerojet reports.

9. Von Elbe, G., "Theory of Solid Propellant Ignition and Response to Pressure Transients," Interagency Solid Propulsion Meeting 3:95 (1963).

10. Hart, R.W., and McClure, F.T., "Combustion Instability: Acoustic Interaction with a Burning Propellant Surface," J. Chem. Phys. 30, 1501-1514 (1959).

11. Ciepluch, C.C., Lewis Research Center, Cleveland, Ohio, Personal Communication, March 1, 1966.

12. Mantilla, R., Baer, A., and Ryan, R., "Extinction by Rapid Depressurization: A Means to Other Ends," 3rd ICRPG Combustion Conference, Cocoa Beach, Florida, Oct. 17-21, 1966.

13. Mantilla, R., Chemical Engineering Department, University of Utah, Salt Lake City, Utah, Personal Communication, Sept. 1966.

TABLE I

PROPELLANT COMPOSITIONS

Propellant Designation	Type	Oxidizer	Metal Fuel	Additive
A	Conventional cast, modified, double-base	AP/HMX=1*	20% Al	--
B	Slurry cast, modified, double-base	AP/HMX=1	5% Al	--
C	Conventional cast, modified double-base	AP/HMX=1	20% Al	--
A-13	Composite, 24% PBAN**	76% 80μ AP	--	--
A-14	Composite, 24% PBAN	76% 15μ AP	--	--
A-15	Composite, 24% PBAN	76% 80μ AP	--	1% copper chromite added
A-16	Composite, 24% PBAN	76% 15μ AP	--	1% copper chromite added
A-17	Composite, 24% PBAN	76% 80μ AP	--	1% LiF added
A-18	Composite, 24% PBAN	76% 15μ AP	--	1% LiF added
G	Composite, 20% PBAA***	80% as received AP	--	--

*AP is ammonium perchlorate

**PBAN is polybutadiene-acrylonitrile

***PBAA is polybutadiene-acrylic acid

TABLE II

EXPERIMENTAL RESULTS

Propellant	Identification	P_o (psia)	P_a (psia)	r_o (in./sec)	$t_{1/2}$ (sec)	Experimentally Extinguished	Theoretically Extinguished	F Value Used	α in.^{2}/sec
Composite	Fig 2 of Ref 5	547	0.1	.27	.0038	yes	yes	0.10	0.00025
A	JO 2**	330	12.7	.361	.0038	yes	yes	0.14	0.00036
A	JO 2**	508	12.7	.433	.0030	yes	yes	0.14	0.00036
A	JO 5**	512	12.7	.434	.0040	no	yes	0.14	0.00036
A	JO 13**	193	0.05	.291	.0043	(borderline) yes	yes	0.14	0.00036
A	JO 18**	486	0.05	.424	.024	yes	yes	0.14	0.00036
A	JO 19**	366	0.05	.378	.026	yes	yes	0.14	0.00036
A	JO 29**	159	0.05	.268	.040	no	no	0.14	0.00036
A	JO 30**	319	0.05	.358	.046	no	no	0.14	0.00036
A	FTM 428**	200	0.00	.295	.018	yes	yes	0.14	0.00036
A	FTM 435**	300	0.00	.348	.017	yes	yes	0.14	0.00036
B	JO 37**	407	0.05	.500	.018	no	no	0.14	0.00036
C	JO 54**	442	0.05	.41	.022	yes	yes	0.14	0.00036
C	JO 55**	420	0.05	.40	.034	no	no	0.14	0.00036
C	JO 63**	313	12.5	.34	.033	no	no	0.14	0.00036
C	JO 64**	297	12.5	.144	.0107	no	no	0.13	0.00023
A-13	10*	165	12.5	.144	.0107	no	no	0.13	0.00023
A-13	15*	164	12.5	.143	.0100	yes	yes	0.13	0.00023
A-13	16*	167	12.5	.145	.011	no	no	0.13	0.00023
A-13	18*	383	12.5	.222	.0091	no	no	0.13	0.00023

TABLE II (CONT.)

EXPERIMENTAL RESULTS

Propellant	Identification	P_o (psia)	P_a (psia)	r_o (in./sec)	$t_{1/2}$ (sec)	Experimentally Extinguished	Theoretically Extinguished	F Value Used	α in.^{2}/sec
A-13	20*	440	12.5	.237	.0061	yes	yes	0.13	0.00023
A-13	21*	292	12.5	.193	.012	no	no	0.13	0.00023
A-13	22*	93	12.5	.107	.0105	yes	yes	0.13	0.00023
A-13	24*	89	12.5	.104	.012	no	no	0.13	0.00023
A-14	34*	158	12.5	.248	.0057	yes	yes	0.17	0.00023
A-14	35*	148	12.5	.238	.0085	no	no	0.17	0.00023
A-14	39*	305	12.5	.41	.0056	yes	yes	0.17	0.00023
A-14	40*	260	12.5	.37	.0085	no	yes	0.17	0.00023
A-16	44*	319	12.5	.665	.0016	yes	no	0.57	0.00023
A-16	46*	320	12.5	.665	.0022	no	no	0.57	0.00023
A-15	55*	275	12.5	.30	.0053	yes	no	0.40	0.00023
A-15	56*	294	12.5	.312	.0075	no	no	0.11	0.00023
A-17	60*	166	12.5	.120	.0079	no	yes	0.11	0.00023
A-17	61*	174	12.5	.122	.0067	yes	yes	0.11	0.00023
A-18	66*	144	12.5	.174	.0062	yes	yes	0.11	0.00023
A-18	67*	170	12.5	.188	.0070	no	yes	0.11	0.00023
A-13	68*	245	12.5	.175	.0061	yes	yes	0.13	0.00023
A-13	70*	220	12.5	.165	.0071	yes	yes	0.13	0.00023
A-13	71*	268	12.5	.182	.010	no	no	0.13	0.00023
G	119*	120	12.5	.170	.0068	yes	no	0.17	0.00027
G	129*	136	12.5	.183	.0085	no	no	0.17	0.00027

*end burner
**opposed slabs

TABLE III

RARIFACTION TUBE RESULTS

Propellant	P_o/P_f	n	F
A-13	1.265	0.51	0.13
A-14	1.29	0.61	0.17
A-15	1.87	0.53	0.40
A-16	2.24	0.56	0.57
A-17	1.29	0.42	0.11
A-18	1.204	0.57	0.11
G	1.306	0.58	0.17

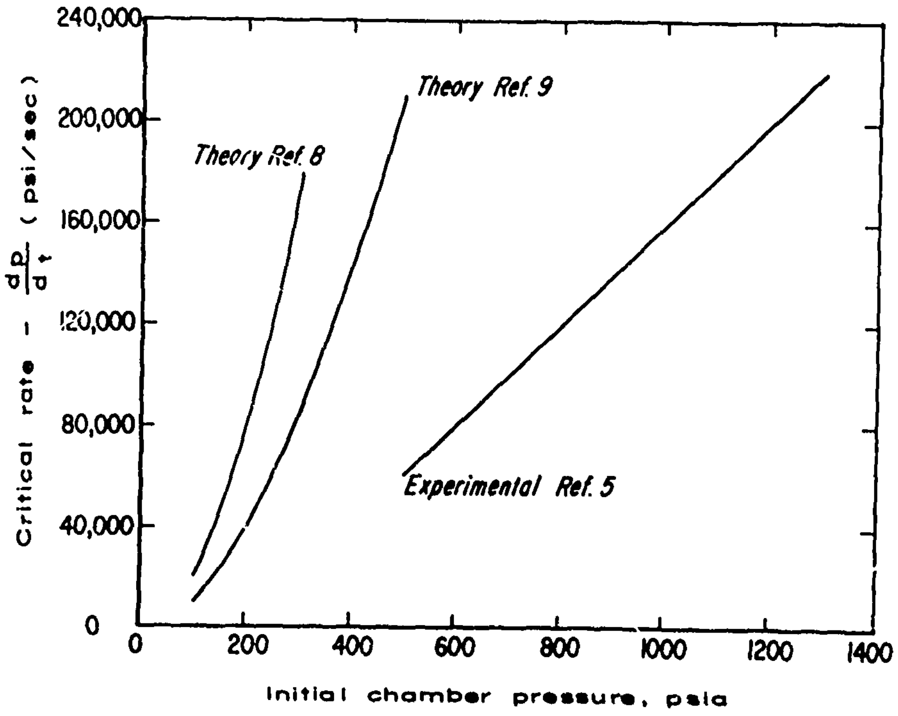

Figure 1 COMPARISON BETWEEN THEORY AND EXPERIMENTAL EXTINCTION CRITERION

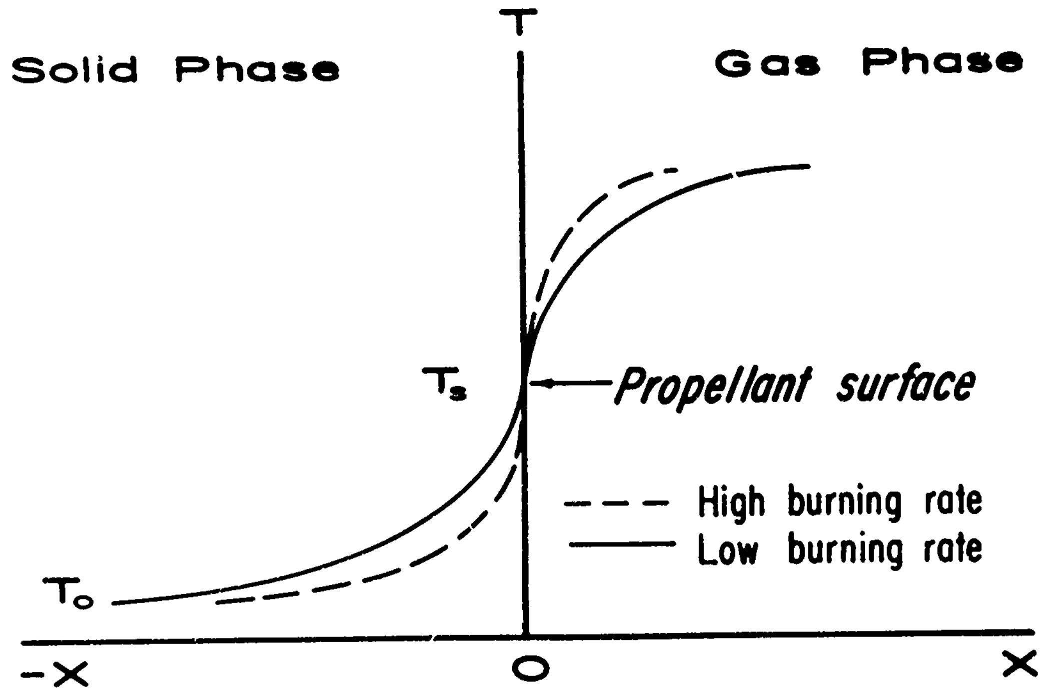

Figure 2 TEMPERATURE PROFILE IN SOLID PROPELLANT

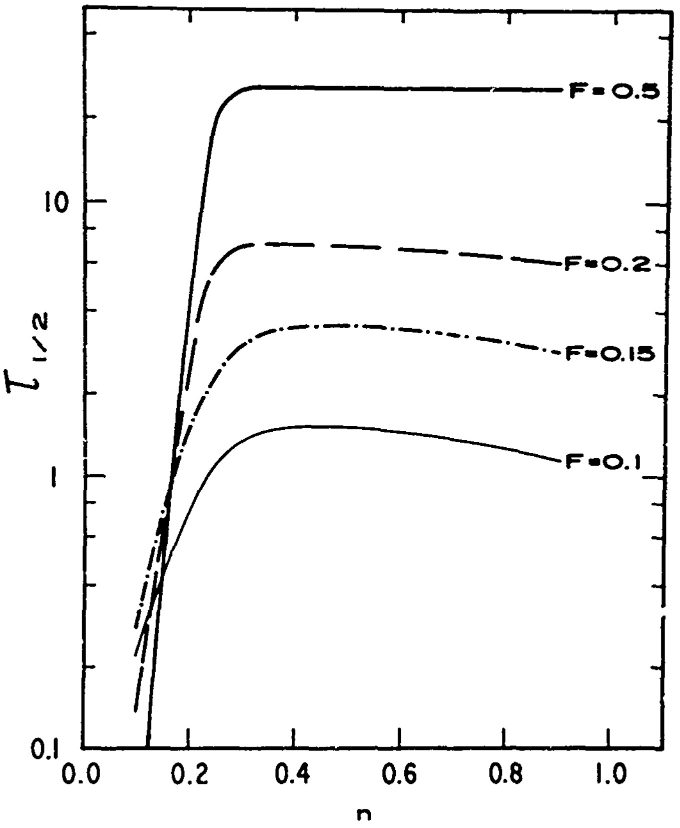

Figure 3 THE MAXIMUM DIMENSIONLESS TIME IN WHICH THE CHAMBER PRESSURE CAN EXPONENTIALLY DECAY TO HALF THE VALUE AND STILL THEORETICALLY CAUSE THE PROPELLANT COMBUSTION TO EXTINGUISH FOR AN AMBIENT PRESSURE OF ZERO.

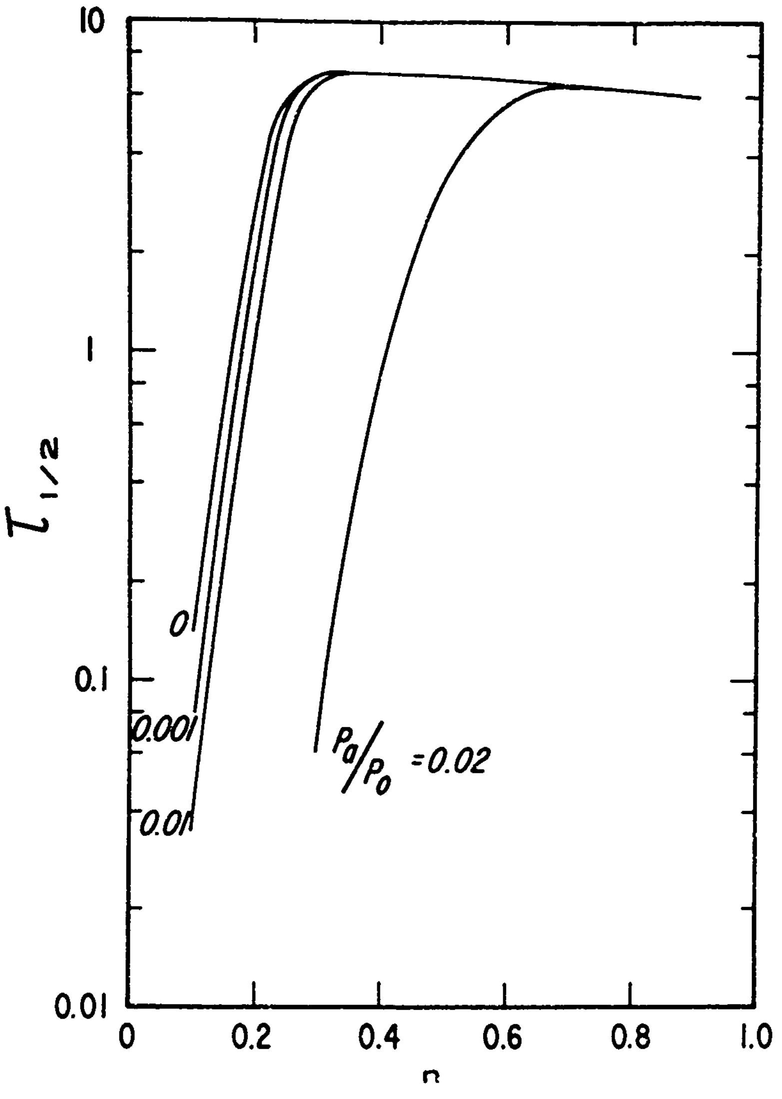

Figure 4 THE MAXIMUM DIMENSIONLESS TIME IN WHICH THE CHAMBER PRESSURE CAN EXPONENTIALLY DECAY TO HALF THE INITIAL VALUE AND STILL THEORETICALLY CAUSE THE PROPELLANT COMBUSTION TO EXTINGUISH FOR AN F VALUE OF 0.2.

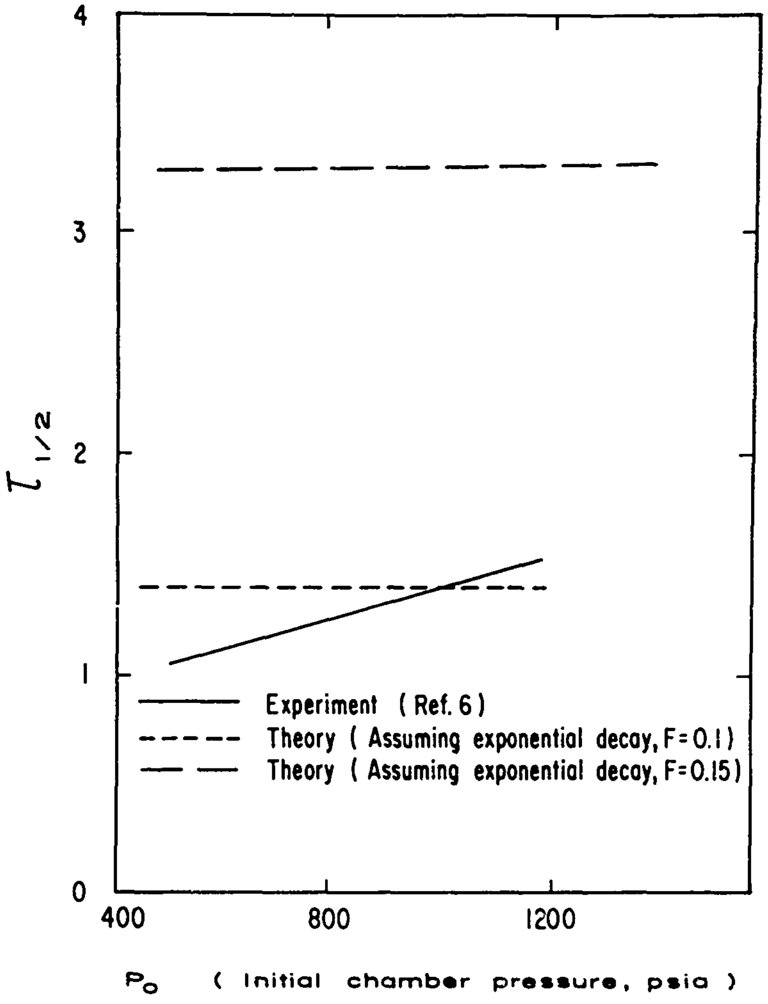

Figure 5 THE MAXIMUM DIMENSIONLESS TIME IN WHICH THE CHAMBER PRESSURE CAN DECAY TO HALF THE INITIAL VALUE AND STILL EXTINGUISH THE PROPELLANT COMBUSTION.

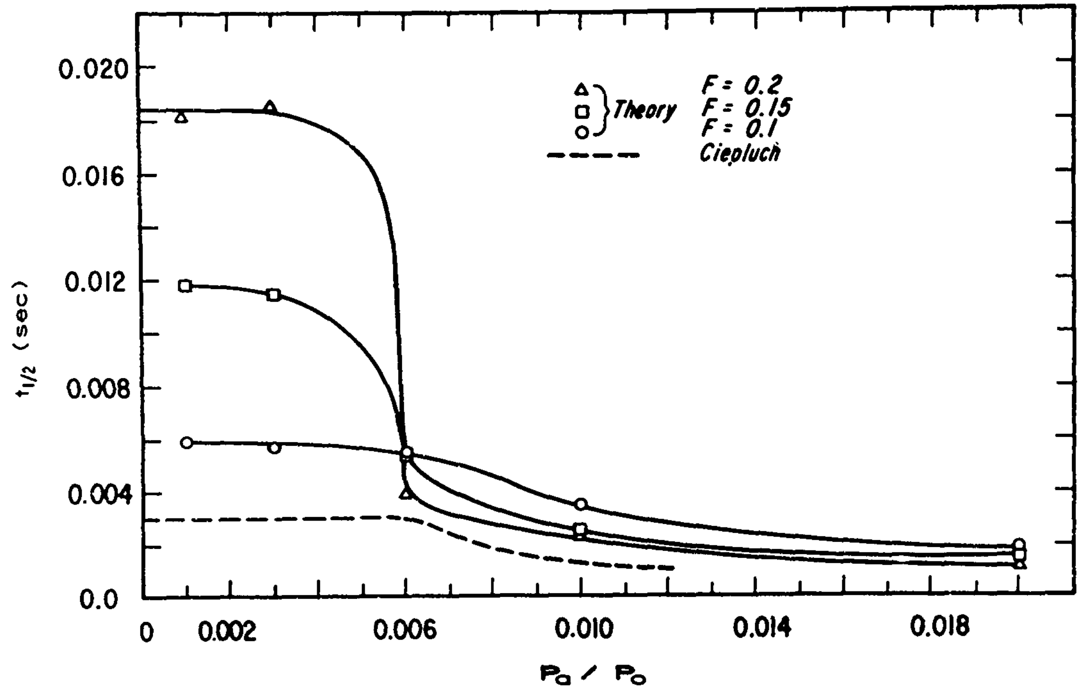

Figure 6 THE MAXIMUM TIME DURING WHICH THE CHAMBER PRESSURE CAN DECAY TO HALF THE INITIAL VALUE AND STILL EXTINGUISH THE PROPELLANT COMBUSTION. THE THEORETICAL VALUES ASSUME EXPONENTIAL PRESSURE DECAY.

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13. ABSTRACT

This paper presents the results of a combined theoretical and experimental study of the process in which solid propellant combustion is terminated by a rapid drop in pressure. Experimentally, propellant burning in a small rocket motor was subjected to a rapid pressure drop when an auxiliary nozzle sizes for the auxiliary nozzle and the boundary between extinction and non-extinction was determined. The results were then compared to the predictions of the theoretical model which was based on the assumption that extinction occurs when the heat absorption by the solid propellant surface exceeds the heat transfer to the solid propellant surface from the combustion gas. In general, the theoretical predictions agreed well with both the experimental results gathered in the program and those published by other investigators.

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KEY WORDS	LINK A		LINK B		LINK C	
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Propellant Extinction						
Solid Propellant Combustion						
Transient Combustion						

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