AD NUMBER: AD0851090
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AUTHORITY
AFRPL ltr dtd 29 Sep 1971

AFRPL-TR-69-66

FLAME PROPAGATION IN PROPELLANT CRACKS

C.E. PAYNE, CAPT, USAF

TECHNICAL REPORT AFRPL-TR-69-66

APRIL 1969

AIR FORCE ROCKET PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

19

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Charles E. Payne, Capt, USAF

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FOREWORD

This is an interim report of work done at the Air Force Rocket Propulsion Laboratory during the period of November 1967 to December 1967. The work was performed under Project COMETS (Combustion of Metallized Systems), No. 305901AMT. The project engineers on this effort were Captain Charles E. Payne and Lieutenant S. W. Koch. Acknowledgement is made to Staff Sergeant Stanley Pugh for his invaluable assistance.

This report has been reviewed and approved.

CHARLES R. COOKE
Chief, Solid Rocket Division
Air Force Rocket Propulsion Laboratory

ABSTRACT

This is a report of work relating to the spread of solid propellant flames into cracks present in the propellant surface. The tests were performed in a no-flow environment within a high-pressure, windowed combustion bomb. Data was all recorded by high-speed motion picture camera and all test conditions were identical—700 psia, and ambient initial propellant temperature. Test results point to no lower minimum crack width which will exclude flame penetration. The time required for flame entry into cracks decreases with decreasing crack width and propagation rates within a crack increase as crack width decreases.

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FLAME PROPAGATION IN PROPELLANT CRACKS

I. SUMMARY

In response to recent SAMSO interest in solid propellant grain cracks and their influence in motor performance, the AFRPL has conducted a series of tests designed to evaluate the tendency of the flame front to propagate into cracks. The potential of catastrophic motor failure due to case burnthrough associated with burning in cracks certainly warrants a study of this problem. In order to provide rapid response to the request for technology, the tests were conducted on very-small-scale TPH-1011 propellant samples, utilizing available test hardware.

II. OBJECTIVE

The objective of this study was to determine the significance of solid propellant crack dimensions as related to flame front penetration into the crack.

III. STATUS

A total of 11 tests were performed on samples with crack widths of from .002 to .028 inch. The tests were run under 700 psig nitrogen pressure. Data recording was done by high-speed cinematography.

IV. EXPERIMENTAL APPROACH

A. Test Setup

The propellant tests were performed in a Rohm and Haas Micro Window bomb (2 x 4 inches inside dimensions). A schematic of the test setup is shown in Figure 1. The combustion bomb was pre-pressurized to 700 psig with dry nitrogen. The bomb was vented using a .013-inch orfice to reduce smoke obscuration and pressure rise. The sample was

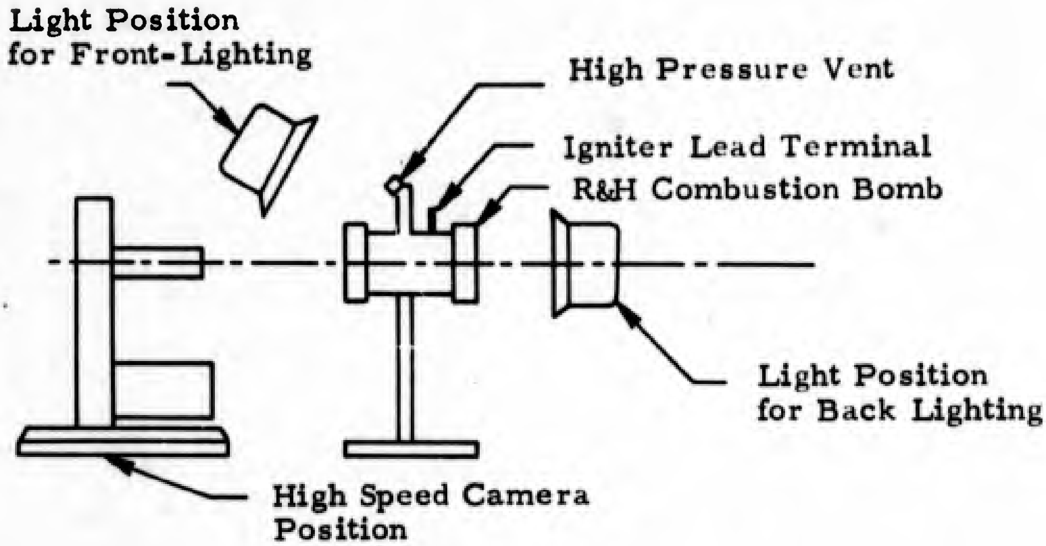

Figure 1. Schematic of Test Setup.

ignited with an electrically heated nichrome wire. The camera lens system and film projection magnification afforded a total image enlargement of approximately 250X. The camera field of view was 3/16 x 3/16 inches.

B. Sample Preparation

The propellant samples used in this evaluation were 3/16 x 5/16 x 1/16 inches. Sample configuration is shown in Figure 2. Samples were cut of TPH-1011 using a microtome and a sharp scalpel. The crack width was set by splitting the sample, bonding the sample to the sample holder with vacuum grease, and adjusting the position of the sample halves using a macroscope with measuring reticle, until the desired crack width was obtained. Several location measurements were made of each crack, as it was never possible to obtain a crack of uniform width. However, the crack width never varied by more than a few thousandths of an inch along its depth.

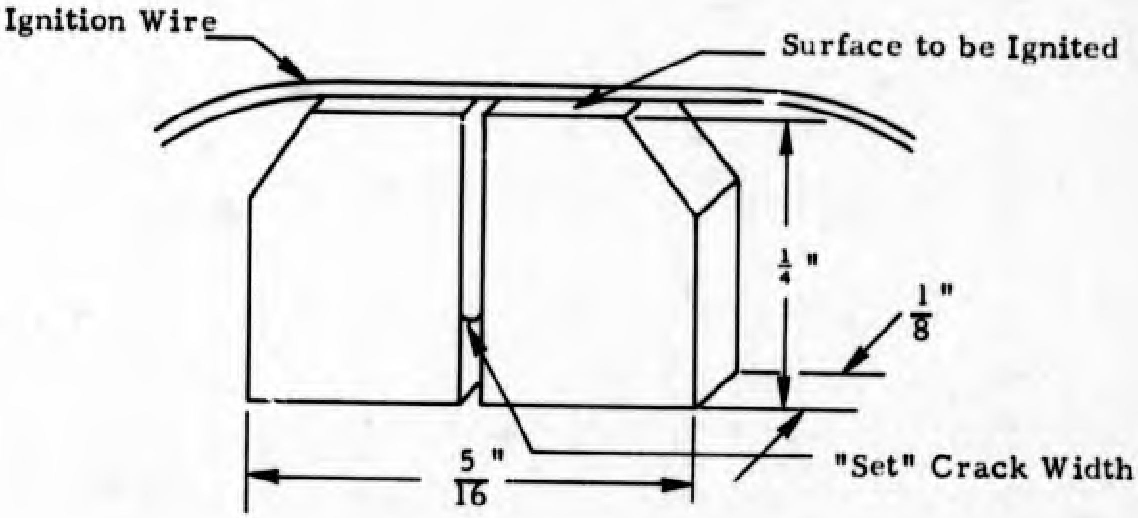

Figure 2. Sample Configuration

C. Test Conditions

All tests were run at 700 psig and there was no gas flow parallel to the sample burning surface. On one test a thin piece of plexiglass was bonded to the camera side of the sample and on another both the front and rear sample surfaces were enclosed by plexiglass. The camera speed was 5000 frames per second for all tests and both front and back lighting tests were run. The film was high-speed color film and was force-processed to an ASA speed of 320. A timing light generator was used and 1000 pips per second were recorded on the film. Samples were prepared with crack widths ranging from .002 in. to .028 in. The crack widths investigated are shown in Table I.

D. Data Analysis

The high-speed cinematography records were analyzed using a Vangard Monel 16 film analyzer. Dimensional reference was made by using the igniter wire which was of known diameter. Time reference was made using the timing marks which were on the frame edges. A qualitive measure of the time for flame entry was made by observing the delay from

TABLE I. CRACK WIDTHS INVESTIGATED

Run No.	Crack Width (.001-in. units)
1	.002 inch
2	.003 inch
3	.004 inch
4	.0075 inch
5	.0010 inch
6	.015 inch
7	.015 inch
8	.020 inch
9	.020 inch
10	.023 inch
11	.028 inch

when the flame reached the edge of the crack until burning was initiated within the crack. Flame propagation rate within the crack was measured by timing light reference and by a coordinate position device associated with the Vangard analyzer.

V. RESULTS

The test results demonstrate that there seems to be no lower limit on crack width that precludes flame entry. The time required for flame entry into cracks decreases as the crack width decreases. Additionally, as crack width decreases there is an increase in propagation rate within the crack.

A. Flame Spread Into a Crack

Measurements of a very qualitative nature were made of the tendency of a solid propellant flame to penetrate into cracks of various widths. The vagaries in the data arise from: (1) the lack of film clarity (the lighting intensity was marginal), (2) the occurrence of interference between the ignition wire and hot aluminum particles which were sometimes deflected into the crack if the wire did not break immediately upon sample ignition, and (3) the uncertainties arising when the sample sometimes ignited, either (a) along the entire top of the samples simultaneously (b) on one top edge of the sample, the flame spreading across from one side only or (c) on either edge of the sample, with the flame spreading to the crack from both sides. As can be seen from the data plotted in Figure 3, there is considerable scatter. However, a trend is fairly apparent. As the crack width decreases, there is a trend towards shorter times for flame entry. The observation is supported by the two extreme cases, the zero-width crack and the infinitely wide crack. Zero-width crack tests were inadvertently run on the two tests where a plexiglass sheet was bonded (with vacuum grease) to the sample face; in both cases the flame penetrated into the bond area between the sample and the plexiglass. The infinite-crack-width test was a subproduct of all remaining tests. The outside faces of the sample are representative of a crack of infinite width and in no case (with TPH-1011 propellant) did the flame burn down the sample faces.

An analytical consideration of the flame penetration phenomenon cannot be made at this time; however, a mechanistic analysis points to hot aluminum particles as the primary energy transport vehicle for the initiation of penetration.

B. <u>Flame Spread Within A Crack</u>

The observed flame spread rates within cracks of varying widths are shown in Figure 4. The line through the data points is an "eye" fit. The curve demonstrates a half order of magnitude increase in flame spread rate as a crack widths decreased from .028 to .002 inch. The data trend is as would be expected from a heat transfer and flow consideration in a channel. The flame spread mechanism can occur by two primary mechanisms. In a nonflow situation, heat is transferred by conduction and radiation from unignited to ignited surface elements. In a flow situation, where flow is parallel to surface elements, the primary method of heat transfer is convective. It is a reasonable assumption that the primary mode of flame spread in a crack is convective heat transfer to the unignited grain. The mass generation in the channel at any given time is represented by:

$$Ab \, \rho_s r_b$$

where:

Ab = area burning in crack

ρ_s = density of solid propellant

r_b = linear burning rate of propellant at crack pressure

This mass flux of generated gas is equal to the mass of gas flowing in the channel at that same time, assuming a steady-state process. The mass flow in the channel is given by:

$$A_{cx} \rho_g V_g$$

where:

A_{cx} = cross section of the crack

ρ_g = density of gas in the crack

V_g = velocity of gas

Equating these expressions:

$$Ab \rho_s r_b = A_{cx} \rho_g V_g$$

$$V_g = \frac{Ab \rho_s r_b}{\rho_g A_{cx}} = G(t,x) \frac{1}{A_{cx}} \qquad G(t,x) = \frac{Ab \rho_s}{\rho_g} = \text{a function of time and position}$$

The cross sectional area of a parallel walled crack of unit length is equal to the crack width and

$$V_g = G(t,x) \frac{1}{Wc} \qquad Wc = \text{crack width}$$

Therefore, for convective heat transfer the velocity of the gas and hence the heat-transfer coefficient are related to the reciprocal of the crack width. The gas velocity, Reynolds Number, heat-transfer coefficient, and hence flame progation rate would be expected to increase as crack width decreases. A linear relationship would not be expected, since the heat-transfer coefficient is related to the .8 power of the gas velocity for turbulent flow. Additionally, all the gas generated within the crack does not flow down the crack. A more complete analysis could be made of the flow fields if the sides of the crack had been restricted in all tests.

VI. CONCLUSIONS

For the test conditions imposed during this program, the tendency of a flame to enter cracks of varying widths increases as crack width decreases. Additionally, the flame propagates faster within cracks of decreasing width. It should be emphasized that these tests were run under a no-flow environment and, in all but two cases, with a crack unrestricted along its depth. The flame propagation phenomenon is explainable through heat transfer, flow considerations. The flame penetration phenomenon is a more complex problem and would require more experimentation to envolve an explanation.

VII. RECOMMENDATIONS

The following recommendations are made relative to future testing of propellant cracks.

a. In order to more carefully define the problem of flame penetration to the case wall, samples should be run which have cracks that do not "bottom out" on the test holder.

b. In order to more carefully evaluate the effects of a motor environment, tests should be run in which there is a flow field parallel to the crack along the propellant surface.

c. Crack samples should be tested which have a more realistic length-to-depth ratio. In this test series the cracks were always short, that is, the crack length was always approximately 1/16 inch, whereas in a motor the crack might be several inches long.

VIII. FUTURE PLANS

Tentative tests are planned utilizing samples enclosed in plexiglass tubes. These tests would essentially meet the recommendations mentioned in the previous section. The accomplishment of these tests is dependent upon the normal work load associated with the COMETS in-house program, under which these tests were performed.

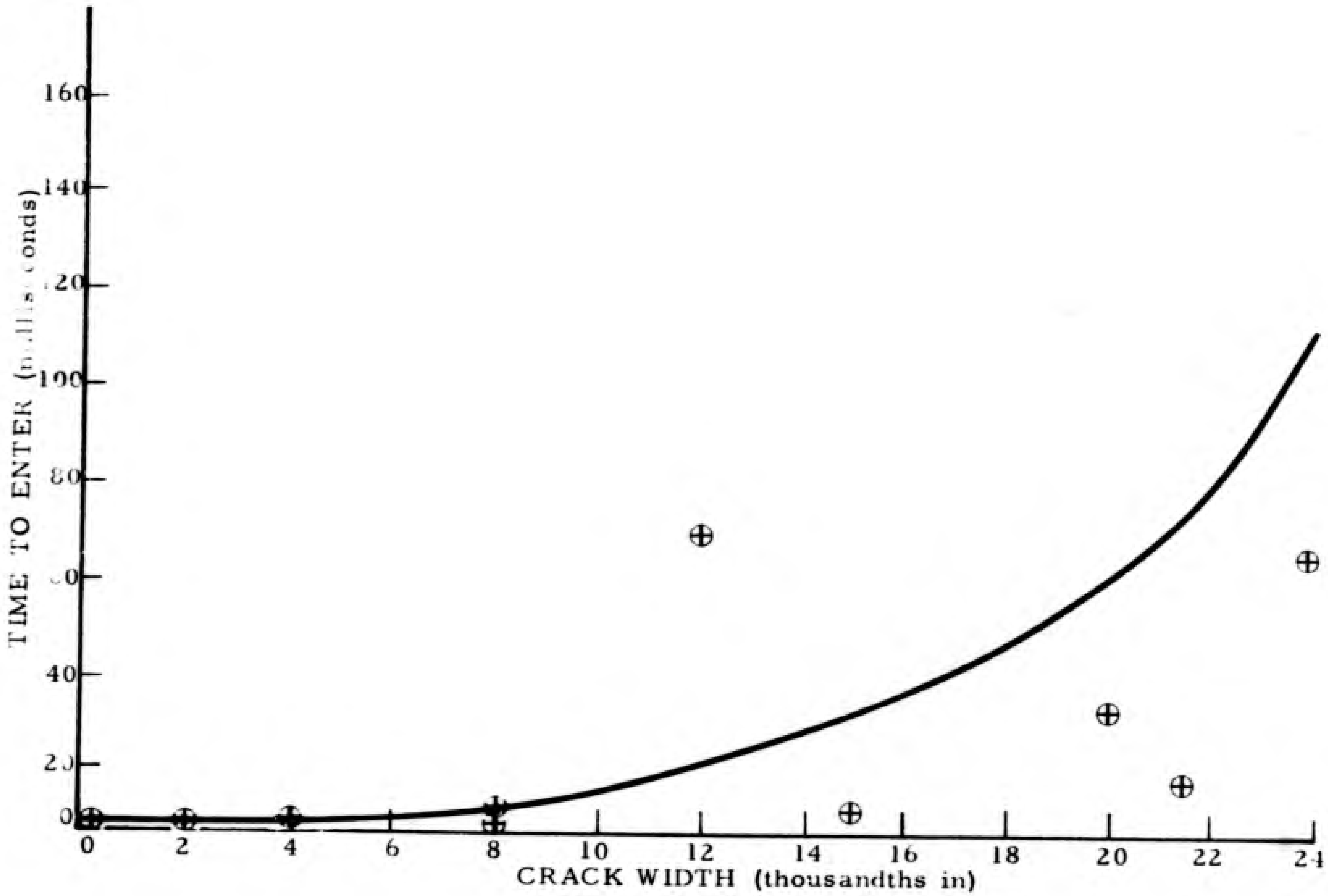

Figure 3. Time to Enter Crack versus Crack Width

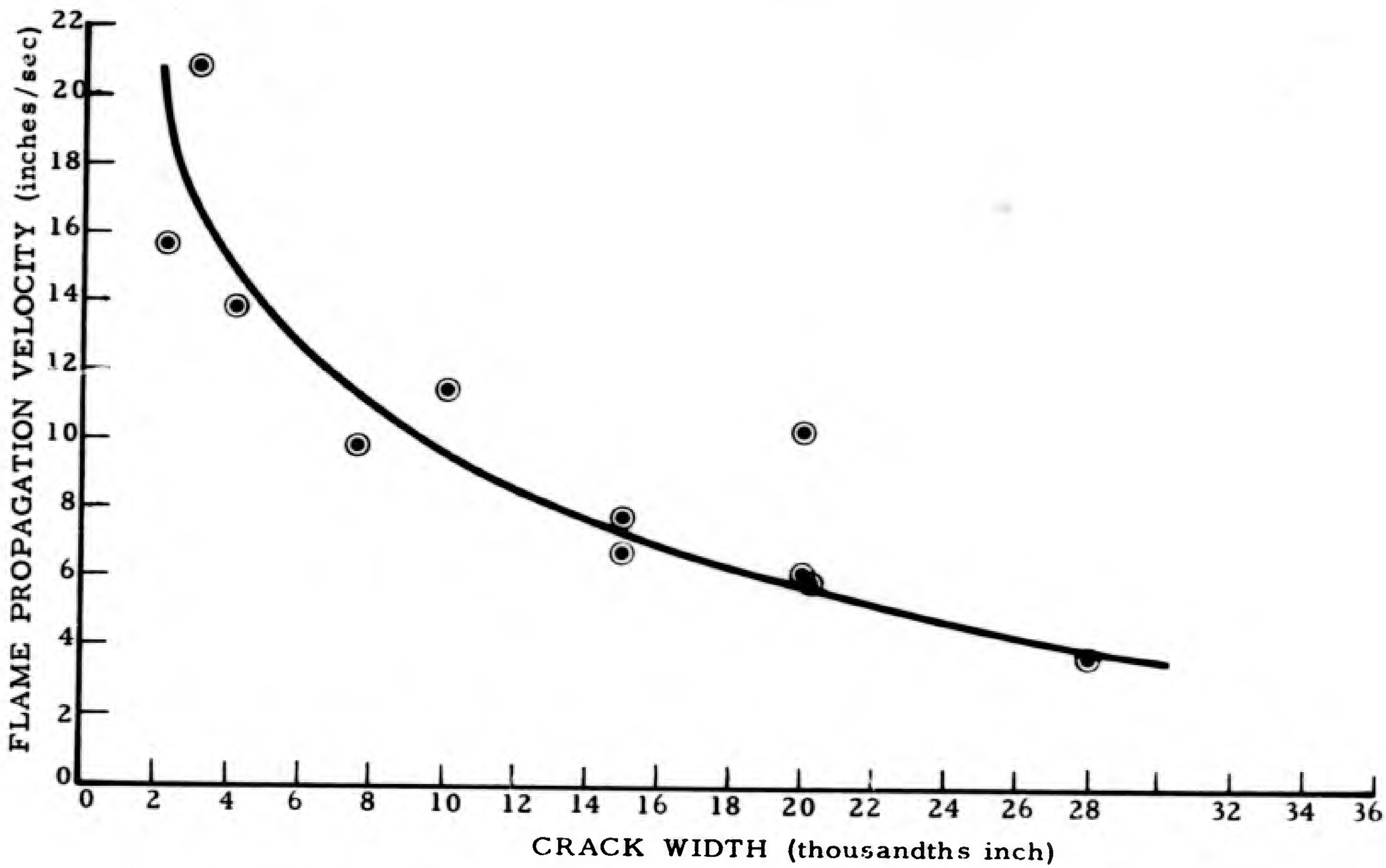

Figure 4. Flame Propagation Rate versus Crack Width

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Rocket Propulsion Laboratory Edwards, California 93523	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

Flame Propagation in Propellant Cracks

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Interim report November 1967 to December 1967

5. AUTHOR(S) (First name, middle initial, last name)

Captain Charles E. Payne

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1969		None

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 3059	AFPRL-TR-69-66
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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DD FORM 1 NOV 65 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flame Spread Solid Propellant combustion Flame propagation rate						