Novel High Area Ratio T-Burner for Characterizing Metalized Propellants

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Special T-burner techniques are needed to characterize metalized propellant. T-burner configurations used previously involved placing a portion of the burning surface in a region of finite acoustic velocity. This is an undesirable situation when only pressure coupled unstable combustion is being sought. Placement of the burning surface at the pressure antinode by expanding the end of the burner tends to excite pressure coupled instability preferentially. Such a configuration is studied. A comparison between the resultant growth constants and the growth constants measured in the variable area T-burner using cups and cylinders is made for a metalized propellant. Within the scatter of the data there is no marked influence of grain orientation on the growth constants. The success of characterizing metalized propellants using this variation of the T-burner lends itself to the investigation of the influence of grain design on unstable combustion.

Nomenclature

L_T	= length of T-burner
S_b/S_{co}	= ratio of burning surface area to T-burner cross-sectional area
S_{co}/S_c	= ratio of T-burner cross-sectional area to port cross-sectional area
α	= exponential growth constant characteristic of pressure oscillations
$\bar{r}$	= mean burning rate
$\bar{P}$	= mean pressure of T-burner
f	= frequency of pressure oscillations
S_b	= burning surface area
V	= volume of the T-burner
$(S_b/S_{co})_{eff}$	= effective area ratio
$VATB$	= variable area T-burner
$EEA\text{-}TB$	= extended end area T-burner
P'	= acoustic pressure
S_{be}	= burning surface area normal to the principal acoustic wave
γ	= ratio of heat capacities of the gases
μ/ε	= propellant response function
M_b	= Mach number of gases leaving the burning surface
α_d	= damping constant for particulate matter and the T-burner walls
$S_{y\cdot x}$	= variation (1 standard deviation) about regression line
β	= dimensionless length of propellant grain; length of lateral propellant surface/half of T-burner length

I. Introduction

THE problem of unstable burning of solid propellants has existed since the development of solid propellant rockets. Recent advances have been made in the methods of characterizing unstable combustion of propellants.[1-3] However, much more needs to be known about the phenomena before the instability of real motors can be predicted.[3] Metalized propellant particularly presents a challenging problem because the large particulate damping often prevents the spontaneous growth of pressure oscillations if conventional T-burner configurations are used. Variations of the original T-burner configuration were suggested as a practical method of achieving spontaneous growth of the pressure oscillations.[4-6] Additional variations of the T-burner have been used to characterize unstable combustion of metalized propellant.[7] Characterization of propellant in a T-burner which oscillated in the Helmholtz mode was proposed by Price 15 years ago.[8]

Two techniques which have recently been investigated for characterizing unstable burning of metalized propellants are the variable area and pulsed variable area methods.[9,10] In the variable area method, a large portion of the burning propellant is placed along the lateral sides of the burner. By increasing the lateral surface area, the total driving due to propellant combustion is large enough to overcome the large particulate damping and to produce spontaneous growth of the oscillations. The extended lateral surface area configuration tends to increase this surface at the expense of the normal burning surface. This limitation comes about due to the end of the T-burner being the same diameter as the tube. It is difficult to vary the end burning surface over a wide range such that high confidence in this driving contribution can be achieved. The pulsed variable area method relies on the intrusion of a relatively large amplitude disturbance to perturb the combustion. The burning surface area is too small to produce spontaneous growth of the oscillations. Each of these techniques has limitations which need to be removed or characterized before the combustion scaling parameter(s) can be determined.

The early work of Hart and McClure et al.[2,11] clearly shows the complexity of modeling the combustion. Culick[12] has shown that the analysis by Hart and McClure should be re-examined for acoustic and mean flow effects. Recent work by Culick suggests that grain orientation is an important factor and that different modeling functions should be used for lateral and normal surfaces.[12,13] The exact form of the modeling functions required for both surfaces is not yet established. The anticipated differences are to be determined experimentally by placing more burning surface parallel or normal to the principal acoustic waves. An experiment of this type has been performed. The results are discussed in this paper. A comparison is made with the data from an extended lateral surface area burner (which will be referred to as the variable area T-burner simply as a matter of convenience).

The main idea behind the test program was to measure growth constants in a configuration which has relatively large areas at the acoustic pressure antinode. This configuration was obtained by fitting large diameter end plates to each end of an existing T-burner. A contoured transition section or a sharp edged entrance

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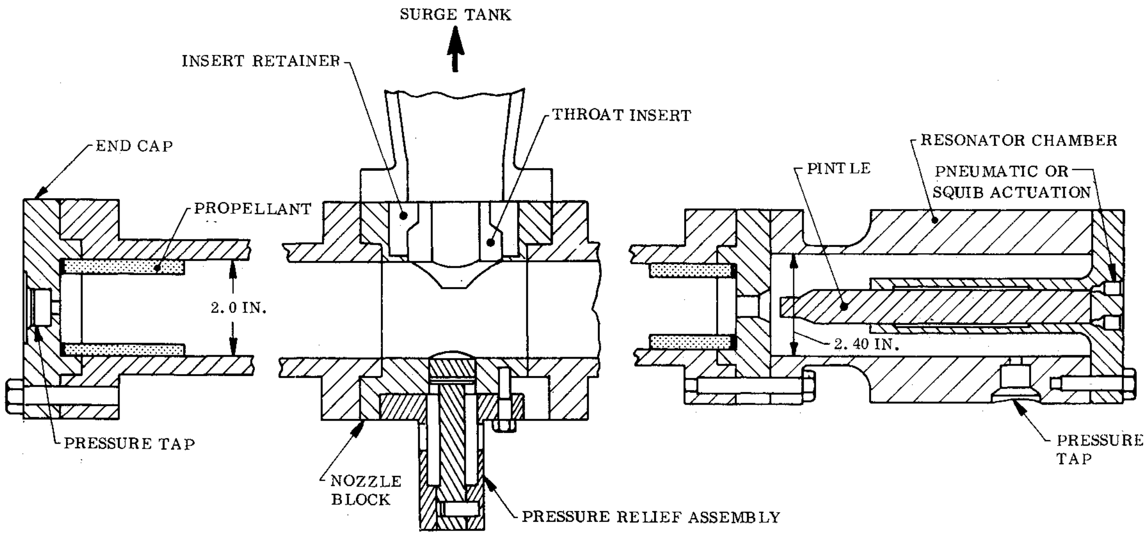

Fig. 1 Variable area T-burner configuration with Helmholtz resonator.

to the T-burner tube could also be utilized. The configurations obtainable in the extended end burning surface area T-burner include a wide variation of the end area. Both forward facing and backward facing grains can be used. The contour of the transition also allows the use of burning surfaces which are neither normal nor parallel to the principal acoustic wave. The tests of the conventional variable area technique can have an appreciable fraction of the burning surface located where the acoustic velocity is finite. The tests described herein minimize the area exposed to a finite acoustic velocity. Five configurations were tested in modified T-burner hardware. These configurations include some extremes with respect to the geometric variables. The results are used to compare the influence of orientation of the burning surface on the growth constant.

II. T-Burner Configurations and Testing Procedures

The basic configuration of the variable area T-burner in which cup and cylinder grain configurations can be tested is shown in Fig. 1. The burner tube has an inner diameter of 2.0 in. Various lengths of tube are available which can be attached to the center block such that the desired frequency is obtained. For tests in which cup and cylindrical grains are used, the length of the burner is adjusted to compensate for large changes in frequency produced by grain volume differences. A Helmholtz resonator cavity was coupled to one end of the burner to control the onset of the oscillations until a preset time is reached. The other end of the T-burner contains a pressure transducer for monitoring the pressure oscillations.

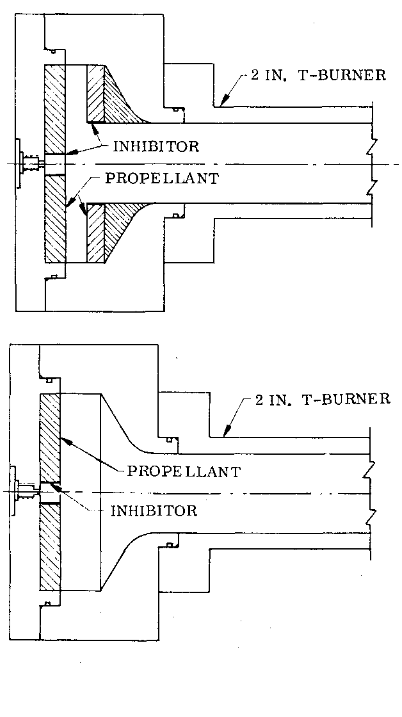

Fig. 2 Extended end area T-burner configuration.

The center block contains a subsonic vent machined from a graphite insert. A Conax fitting is also placed in the center block to accommodate the ignition wires. Ignition is produced by bag igniters containing $BKNO_3$ pellets and squibs. Essentially constant pressure is maintained by connecting the burner to a large surge tank.

The configuration of the extended end area burner (*EEA-TB*) is shown in Fig. 2. It consists of a 2.0 in. diam steel tube connected to extended area sections at each end which are 5 in. in diameter. The transition section between the 5 in. tube and the 2 in. tube can be either contoured or sharp edged. Propellant can be placed along the walls of the transition section of the burner or at the ends of the burner.

The pressure oscillations are monitored by using a Kistler 603A piezoelectric transducer. The data was recorded on an Ampex FR1300 FM tape deck for later processing. Playback of the signal was through two sections of SKL 302 variable electronic filter and onto an oscillograph recorder. Peak-to-peak pressure amplitude vs time was plotted on semilog paper. The linear portion of these plots was then used to determine the growth constant.

Figure 3 shows the grain configurations tested. It was to avoid the effect of the finite acoustic velocity parallel to the surface that the extended end area burner (*EEA-TB*) configurations were tested. Three variations of the extended end area T-burner were tested. These configurations included the simple end disk with a contoured contraction, two end disks in an opposing face configuration, and a six-point star grain placed in the large diameter ends of the burner. A metalized composite propellant containing 88% solids and 15% aluminum was used in these tests.

The tests were all made at or near 500 psi and 800 Hz. The actual test conditions are indicated in the data summary. The conditioned temperature for all tests was 70° ±10°F.

Rather extensive experimentation with this particular propellant has been completed using the variable area technique, pulsed T-burner technique and the pulsed/variable area T-burner technique. Data from these tests provide a good basis from which to compare the extended end burning area T-burner.[9,10,14-16]

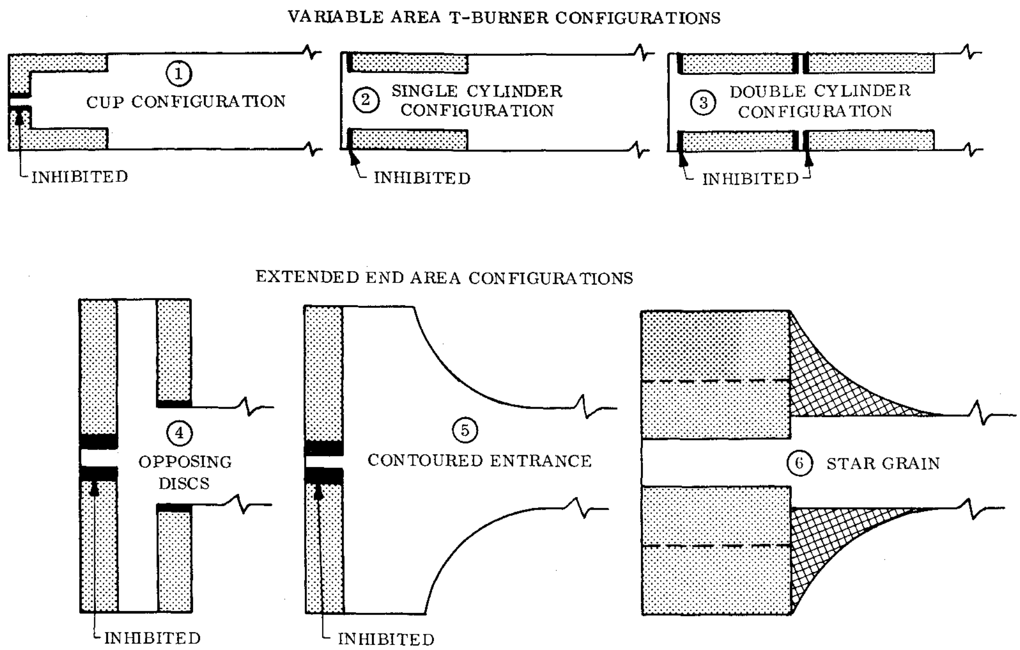

Fig. 3 T-burner configuration tested to achieve spontaneous oscillations.

III. Test Results

The results of the extended end area T-burner tests are summarized in Table 1. The area ratios shown in Table 1 are defined in the footnote. These correspond to the condition at the time the growth constant was measured. The configuration identification is indicated on Fig. 3.

Experimental results for the extended lateral area T-burner tests (*VATB*) are summarized in Table 2. Double lengths of cylindrical grains were used to achieve the high area ratio, S_b/S_{co}. The configurations involving cups and cylindrical grains are shown in Fig. 3.

IV. Discussion of Results

The desired end product of the T-burner testing is the propellant response function. To date, a uniformly acceptable interpretation of the T-burner data has not been prepared. At this point in the development of T-burner data analysis, the simplest method of data presentation and interpretation is used. In the T-burner manual,[6] it is suggested that the slope of the growth constant vs geometric area ratio plot should be proportional to the propellant response function. This is based on the assumption that mechanisms of and the magnitudes of the loss of acoustic energy are the same for all values of the area ratio, S_b/S_{co}. The experimental growth constant is plotted as a function of the geometric area ratio in Fig. 4. If all the burning surface is normal to the principal acoustic wave, the slope of the curve is proportional to the response function. A plot of the combined cup and cylinder grain data for the *VATB* tests and the three configurations of the *EEA-TB* tests is shown in Fig. 4. The data in Fig. 4 exhibit wide scatter in growth constant at constant geometric area ratio. At area ratios above seven, the data scatter

Table 1 Summary of extended end burning area tests

Configuration identification	Area Ratio S_b/S_{co}	Area Ratio S_{co}/S_c	Mean burning rate (in./sec)	Mean pressure (psi)	Frequency (Hz)	Growth constant (sec^{-1})
5	6.19	0.16	0.32	522	0	0
5	6.19	0.16	0.34	522	0	0
4	11.13	0.16	0.35	555	700	105.9
4	11.13	0.16	0.32	565	700	63.0
4	9.88	0.16	0.35	540	700	62.3
4	9.88	0.16	0.35	540	640	50.6
6	5.44	1.14	...	552	910	44.1
6	5.48	0.66	...	552	850	18.4
6	5.44	1.14	0.30	552	890	35.5
6	5.48	0.66	0.30	552	825	9.5
4	9.88	0.16	0.36	528	700	56.5
4	9.88	0.16	0.36	528	650	45.6
4	11.13	0.16	...	530	750	104.6
4	11.13	0.16	0.36	543	750	115.3
4	11.13	0.16	0.35	530	710	93.2
4	11.13	0.16	0.35	537	720	100.4

Table 2 Variable area T-burner data

Run No.	Area Ratio S_b/S_{co}	Area Ratio S_{co}/S_c	Dimensionless grain length (β)	Frequency (Hz)	Growth constant (sec^{-1})
Cups					
B2B	5.09	2.08	0.22	800	86.5
B16B	8.25	2.02	0.37	760	97.6
B15B	8.23	2.03	0.37	750	80.1
B14B	6.57	2.01	0.28	740	92.4
B13B	6.52	2.05	0.29	730	55.7
B12B	5.13	2.05	0.21	800	87.1
B10B	3.54	2.08	0.13	750	8.8
B9B	3.55	2.06	0.13	750	10.8
B7B	4.23	2.09	0.17	780	26.1
B6B	4.22	2.09	0.17	780	33.7
B5B	4.26	2.04	0.17	767	30.5
Cylinder					
B17A	3.62	3.3	0.2	800	34.3
B17B	4.11	1.99	0.19	770	31.4
B18A	3.59	3.4	0.2	800	32.4
B18B	4.08	2.06	0.19	780	33.1
B19A	3.61	3.3	0.2	800	29.6
B19B	4.07	2.07	0.19	770	30.8
Double cylinders					
B41A	6.97	3.23	0.37	800	69.9
B41B	8.24	2.07	0.36	740	122.2
B42A	6.87	3.37	0.37	800	70.6
B42B	8.27	2.05	0.36	740	104.8
B43A	6.84	3.40	0.37	800	69.6
B43B	8.28	2.05	0.36	735	105.4

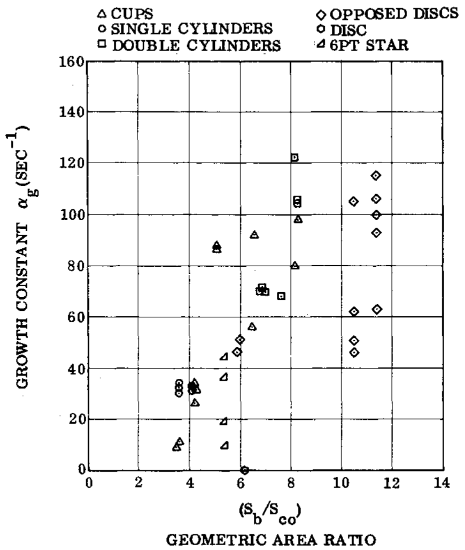

Fig. 4 ***VATB*** **and** ***EEA-TB*** **growth constants measured for a metalized propellant vs geometric area ratio.**

increases for each configuration tested. This is particularly noticeable for the *EEA-TB* configuration using the two opposed disks, configuration 4 in Fig. 3. Below an area ratio of about six, the data scatter is also large if all data are included.

Following suggestions of Hart and McClure, the data are replotted in a variable which reflects the acoustic pressure distribution over the burning surface. The data are shown in Fig. 5. In the notation of the T-burner manual, the growth constant is given by

$$\alpha = 2(\bar{a}/L)M_b[\gamma(\mu/\varepsilon)](S_b/S_{co})_{eff} - \alpha_d$$

where the effective area ratio is defined as

$$(S_b/S_{co})_{eff} = L/4[\int(p')^2 dS_b/\int(p')^2 dV$$

The integral in the numerator is evaluated over the burning surface. The integral in the denominator reflects the effect of the burner volume and can also be shown to be related to the acoustic energy of the burner.[14] The acoustic pressure required in the computation of the effective area ratio is determined from the solution of the classical wave equation for the burner configuration at the time the growth constant was measured. The modified one-dimensional treatment was used to compute the acoustic pressure.[14–16]

If there is no difference in the combustion driving due to end and lateral surfaces, and if the particulate damping and the wall damping are independent of the area ratio, then the slope of a plot of the growth constant vs the effective area ratio should be proportional to the propellant response function. The data scatter in Fig. 5 is still large, but there appears to be a better correlation of the data than if the simple geometric area ratio is used to correlate the data. Objective evidence of this improved correlation is shown in Table 3. The combined data for all configurations over the entire area ratio range show less scatter if the effective area ratio is used to correlate the data.

Values of the response function extracted from these data are 0.8 for the *VATB* data and 1.1 for the *EEA-TB* data. The combined data yield a response function of 0.9. Also shown in Table 3 is the Least Squares Regression line for the separate types of T-burner data.

A significant statistical difference does not exist between *VATB* and *EEA-TB* data when S_b/S_{co} is used as a correlating term. A statistical difference (95% confidence) does exist between the two data sets when correlated with $(S_b/S_{co})_{eff}$. The improvement in the correlation is most noticeable for the *EEA-TB* test data. The standard deviation decreases considerably when the correlation with effective area ratio is made as compared to the correlation with the geometric area ratio.

The *VATB* data do not show a corresponding improvement in the correlation between using the effective area ratio and the geometric area ratio. This could indicate that an additional contribution to the growth constant is effective when large lateral surfaces are used. Such a factor could be associated with the finite acoustic velocity over the lateral surfaces.

V. Summary and Conclusion

The tests with the extended end area T-burner demonstrate that consistent, spontaneous growth constants can be obtained with this burner geometry. The advantages of the extended end area T-burner configuration are as follows.

1) End burning surface area is large compared to the burner cross-sectional area, i.e., $S_{be}/S_{co} > 1$.

2) A small lateral burning surface area is subjected to finite acoustic velocity. No modeling of lateral surfaces is required.

3) Multiple growths can be measured in each test by using the Helmholtz resonator suppressor.

4) Combinations of slotted grains and star grains allow for observing the influence of slots on the growth constants.

The larger burning surface area near the acoustic pressure antinode provides enough driving to overcome the losses due to particulate and wall damping. The fact that the burning surfaces

Table 3 **Summary of interpretation of** ***VATB*** **and** ***EEA-TB*** **test data**

	$\alpha = f(S_b/S_{co})$	$\alpha = f(S_b/S_{co})_{eff}$
VATB data, cups and cylinders		
$S_{y \cdot x}$	15.8	20.3
Intercept	−31.9	−1.6
Slope	16.2	8.3
Number of tests	23	23
EEA-TB data		
$S_{y \cdot x}$	19.8	12.4
Intercept	39.3	78.1
Slope	11.4	20.3
Number of tests	14	14
Combined data		
$S_{y \cdot x}$	24.0	20.8
Intercept	0.5	−8.5
Number of tests	37	37

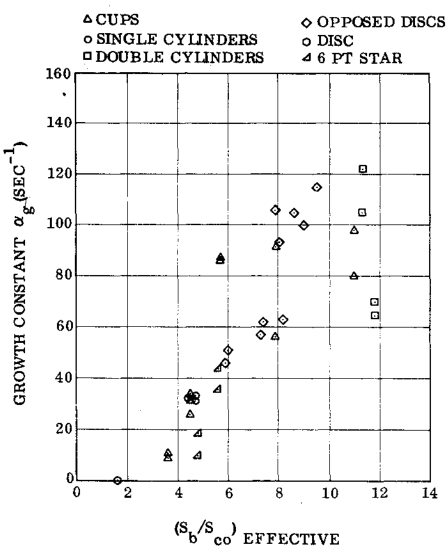

Fig. 5 ***VATB*** **and** ***EEA-TB*** **growth constants measured for a metalized propellant vs effective area ratio.**

are oriented opposite each other in some tests does not seem to influence the results. In Fig. 5, the extended end area tests fit into the general pattern of the data. The data for star grains, opposed disks, cups, and cylinders all correlate reasonably well.

Ignoring the data at an area ratio greater than about six significantly improves the correlation of the data. It may be necessary to ignore the high area ratio data from the *VATB* tests because of velocity coupling effects.

The extended end area burner configuration is an effective way of placing a large burning surface area at locations where the acoustic velocity is small. Using cup or cylindrical grains in the variable area T-burner leads to large changes in both the geometric area ratio and the effective area ratio during a test. The opposed disk configuration of the extended end area burner has constant geometric area ratio during a test.

Further experimentation with this burner configuration could involve tests of the influence of grain geometry and slot dimension and location on the growth constant.

A main conclusion from these experiments is that the grain orientation is not particularly important for low area ratio tests. This suggests that only one parameter is needed to characterize unstable combustion.

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