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RESPONSE OF A BURNING PROPELLANT SURFACE TO EROSIVE TRANSIENTS

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INTRODUCTION AND SUMMARY

Under the previous contract AF 49(638)-1507, it was found that the heat release in the solid phase was associated with the driving process of unstable combustion. Since most of the propellants of interest are based on ammonium perchlorate (which has been shown to endow propellants with instability), it was considered necessary to identify the processes which could attenuate acoustic waves.

To date our study of loss mechanism has shown that end losses are significant and enhance both axial and transverse stability. In the case of axial instability the enhanced heat transfer to the end closure is being examined using heat transfer gages.

Our theoretical studies are continuing in an attempt to integrate combustion response to the gas dynamics of the cavity.

EXPERIMENTAL STUDIES

Axial and Transverse Mode Dampening

During one of our early experiments using a rectangular slab motor, a core became malaligned, and as a result the center rectangular perforation was significantly out of alignment with the axis of the motor. It was decided to test the motor to ascertain whether this was a significant variable affecting either the initiation of axial mode instability or its characteristic response in the motor. On firing it was observed that combustion was stable even though pulsed considerably above the critical pressure predicted from our correlation for AP propellants.

It was postulated that stability was enhanced because the traveling wave, not intersecting normally with the reflecting surface (head end), lost energy after reflection. It was believed possible that certain other internal design factors might cause similar dampening. One proposed design was the introduction of a head end which was deliberately out of alignment. An aluminum wedge 5 inches in diameter was consequently attached to the pulse head in the 5-inch x 50-inch motor in such a manner as to tilt the face 30° from the perpendicular to the axis. The motor was loaded with a radial burning grain of PBAN 103 propellant, which has a critical threshold pressure of 600 psia. During the firing two significant observations were made. First, combustion was stable to 980 psia before the third pulse drove it unstable; during instability the wave form was extremely distorted and appeared to have a large harmonic content. Second, in all of our past testing with PBAN 103, an 80/20 AP/binder propellant, the instability invariably changed from axial to transverse (this normally caused higher chamber pressures and ruptured the nozzle safety bolts). In contrast, the slant head motor remained in the axial mode throughout burning.

The above experiments suggest strongly that energy losses at the ends, in particular the head end, contribute significantly to stability in both the axial and transverse modes. Heretofore the losses at the ends have been considered insignificant and have been neglected in most of the analyses of over-all stability which have so far been published (e.g., the Hart-McClure theory). It is apparent that the viscous drag on the head end is probably a significant source of loss for transverse instability; in the case of traveling wave instability, our data (see next section) suggest that, in relation to the contact time of the shock front, an unexpectedly high rate of heat transfer occurs.

The influence of length to diameter ratio on stability is obviously explained by the fact that as the length decreased the end losses became more significant relative to the driving from the burning propellant.

Heat Transfer During Unstable Operation of a Motor

Heat transfer rates to the head end of a 5-inch x 40-inch motor operating in both the stable and unstable modes have been measured. During axial mode instability the heat transfer rate was approximately 660 BTU ft^{-2} sec^{-1}; during stable combustion it was 90 BTU ft^{-2} sec^{-1}. This high rate of heat transfer at the head end suggests that the inert head end serves as an energy sink and is as efficient as the nozzle in causing appreciable wave pressure losses. At this time it is postulated that the primary mode of energy loss is by radiation. The thermal response of the cool head end is low compared to the frequency of the instability, and therefore the end is seeing an on-coming high temperature shock continuously. This same loss mechanism must operate at the nozzle end; however, it is modified by several factors.

The first factor to be considered at the nozzle end is the influence of the nozzle opening, which is a sink for mass and energy; the second is the two different surface environments interacting with the wave. In our representative test motor the outer annulus behaves somewhat like the head end except for the shape and emissivity (carbon versus steel at head end). The carbon nozzle would nevertheless present a rather cool reflection surface and absorption surface to thermal radiation from an advancing shock. The nozzle opening area is quite different in that the advancing pressure wave sees a high temperature shock front located in the nozzle throat. Radiative heat loss in this case would be expected to be minimized.

Wave Growth Studies - Influence of Aluminum on Gas Dampening

Several experiments were conducted in 5-inch x 80-inch slab motors to measure the wave pressure and velocity at different stations. The propellant variable was aluminum content, 5% versus 15%. With the 15% Al loaded propellant, data were lost due to Kistler gage instabilities induced by high temperature; neither the wave pressure nor velocity profile could be deduced. At the four out of six stations which functioned adequately it was apparent that the wave pressure was significantly reduced; this test has to be repeated. Unfortunately, under the severe conditions of heat transfer, neither motor tube nor pressure gages last very long.

The test with propellant containing 5% aluminum was more successful in that the wave pressure was tracked successfully. However, one gage was lost, and so again the velocity profile could not be deduced. This propellant generated higher wave pressures and exhibited higher gain factors than did the 80/20 AP/binder propellant reported in our Annual Report,[1] Contract No. AF 49(638)-1507. In fact, the heating produced by this instability caused a case burn-through and the loss of two motor cases. We plan to alleviate this difficulty in the future by bonding two strips of silica-loaded buna-N rubber inside the casings along the slot.

In our study of wave pressure and velocity in the 5-inch-diameter motor, it was reported in the annual report[1] that the combustion in the 5-inch x 15-inch motor did not go unstable, and we were unable to track the pulse beyond one cycle. The pulse behaved as though it were influenced by the nozzle attenuation before it ever reached the nozzle. Thus it was postulated that there might be a difference in response between a hot propellant gas and a cold gas. To ascertain whether this is true, the 5-inch x 15-inch motor was cold-flowed with helium and pulsed.

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[1] Capener, E.L., R. J. Kier, L. A. Dickinson, and G. A. Marxman, Response of a Burning Propellant Surface to Erosive Transients, Final Scientific Report, A.F. Office of Scientific Research Contract No. AF 49(638)-1507, March 15, 1966

Helium was chosen because the speed of sound in helium and propellant are approximately the same, 3200 ft/sec. The helium flow rate of 0.23 lb/sec was sufficient to cause choked flow at the nozzle and raise the chamber pressure to 100 psig using the same nozzle as was used with propellant. The gas was introduced at the head end of the motor containing an inert propellant with mechanical properties similar to those of PBAN 103. In both hot propellant gas and cold helium gas the pressure response to the black-powder pulse was nearly identical. In neither case could the wave be tracked beyond one cycle.

Spectral Studies

In further tests with our 2-inch x 20-inch slab window motor we re-designed the pulse tube to reduce the free volume at the head end and removed the entry contour from the nozzle inlet in order to reduce the attenuation. (This is the motor originally used in attempts to examine shock wave structure photographically.) It is planned to examine spectral transmission and emission in association with related studies in extinction.

THEORETICAL STUDIES

A more rigorous derivation of the stability criteria reported under Contract AF 49(638)-1507 has been performed. The conclusions remain unchanged, justifying the interpretation that heat release in the solid phase is not conducive to stable burning. The more rigorous derivation has been achieved by transforming the mathematical description of our combustion model, which includes surface-coupled reactions, to a problem that is mathematically identical to an earlier analysis by Denison and Baum,[2] which excluded surface-coupled heat release. In this way an exact treatment of our combustion model, based on the Laplace transform technique, is obtained by extending an available treatment. By comparing the results with those obtained previously by Denison and Baum for zero surface heat release, the effect of surface-coupled reactions on combustion instability bounds can be evaluated directly. Also, by comparing our simple, approximate solution with the exact solution (which is unwieldy and can be presented only graphically for practical purposes), the limitations of our mathematical simplifications can be determined. Ultimately this may lead to an improved approximate treatment, which gives results close to the exact solution but can be presented in terms of simple equations. This is highly desirable in formulating a practical stability theory.

By comparing our model[1] with that of Denison and Baum,[2] the reader can easily verify that the following transformation of a set of parameters defined by them makes the two models mathematically identical (the subscript DB denotes the parameter as defined by Denison and Baum).

$$\left.\begin{aligned} q &= q_{DB} + \theta_H\left(\frac{E_H}{RT_w} - m\right) + \frac{E_D}{RT_w} \\ B &= B_{DB} + \frac{\theta_H m}{\alpha} \\ \alpha &= \alpha_{DB} \qquad A = A_{DB} \end{aligned}\right\} \quad (1)$$

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[2] Denison, M.R., and E. Baum, "A Simplified Model of Unstable Burning in Solid Propellants," ARS Journal, 31, 1112(1961).

where

$$\theta_H = \frac{H_H}{C_s\overline{T}_w}\left(\frac{P}{T_w}\right)^m \exp\left(-E_H/R\overline{T}_w\right)$$

$$\theta_D = \frac{H_D}{C_s\overline{T}_w} \exp\left(-E_D/R\overline{T}_w\right)$$

The Self-Excited Mode

Equations (1) transform Denison and Baum's solution into a Laplace transform perturbation analysis of our combustion model,[1] in which surface-coupled reactions are permitted. This analysis shows that the response of the combustion mechanism to pressure perturbations has two separate modes, the "self-excited" mode, and the steady oscillatory mode. The bounds of the self-excited mode are illustrated in Figs. 1-4 for selected values of the surface-coupled exotherm parameter, θ_s, where

$$\theta_s = \left(\frac{E_H}{R\overline{T}_w} - m\right)\theta_H + \frac{E_D}{R\overline{T}_w}\theta_D$$

$$\theta_H = \frac{H_H}{C_s\overline{T}_w}\left(\frac{P}{\overline{T}_w}\right)^m \exp\left(-E_H/R\overline{T}_w\right) = \frac{Q_H}{Q_T}\left(\frac{T_w - T_o}{T_w}\right) \qquad (2)$$

$$\theta_D = \frac{H_D}{C_s\overline{T}_w} \exp\left(-E_D/R\overline{T}_w\right) = \frac{Q_D}{Q_T}\left(\frac{T_w - T_o}{T_w}\right)$$

Note that θ_s is a measure of the fraction of the total heat flux into the grain that comes from surface-coupled heterogenous and decomposition reactions; Q_T is the total heat flux from gas-phase and surface-coupled reactions; Q_H is the heat flux from heterogeneous (pressure-sensitive) reactions, and Q_D is that from decomposition (pressure-insensitive) reactions. When $\theta_s = 0$, all energy release occurs in the gas phase, and the corresponding curves in Fig. 1 are those generated by Denison and Baum. For typical values of the activation energies and surface temperature, $E_H/RT_w \sim 20$ and $E_D/R\overline{T}_w \sim 20$. Thus if

$Q_H/Q_T \sim 0.02$ and $Q_D/Q_T \sim 0.02$, so that surface-coupled reactions provide 4 percent of the total heat flux to the grain, the values of θ_s is about 0.4. As a first approximation, one can conclude that the magnitude of θ_s is of the order of ten times the fraction of total heat flux coming from surface couple reactions. For example, Fig. 2 corresponds to a propellant in which about 5 percent of the total heat release is generated in the surface zone, while close to 1/3 of the total is attributed to this source in Fig. 4.

For each value of θ_s the self-excited mode is separated into three distinct regions, labeled a, b, and c on Figs. 1-4. The thermochemical constants of the propellant, which appear on the ordinate and abscissa of Fig. 1, determine the nature of the response of that propellant. In region a, the pressure perturbation causes the self-excited burning rate mode to respond as an exponentially decaying oscillation; i.e., the self-excited mode is stable. In region b, the response is an exponentially increasing oscillation, and in region c, it is a monotonic exponentially increase in amplitude. Thus, for a given Q_s (or percentage of surface-coupled heat release), a propellant that falls in either region b or c will be unstable. From a different viewpoint, a propellant with given thermochemical constants may be either stable or unstable, depending on the extent of the surface-coupled exotherm. For example, a propellant with $A_{DB} = 3$, $1/\alpha_{DB} = 1.5$, would be stable if $Q_s = 0.5$, but unstable if $Q_s = 3$.

The stability limit for each value of θ_s is the curve that separates region a (the stable zone) from regions b and c in each of the figures. In zones b and c a pressure disturbance of any frequency or type will induce unstable combustion in the self-excited mode, with an oscillatory response in b, and a monotonic response in c. In region a the amplitude of the self-excited mode of response tends to decay with time, so that this mode is stable.

In Fig. 5, the stability bounds (limits on region a) for $\theta_s = 0$, 0.5, 1, and 3 are shown together. This figure illustrates the rather drastic effect on stability characteristics which arises with even a relatively minor appearance of exothermic surface-coupled reactions. If as little as 5% of the total heat release occurs in such reactions, the extent of the stable-operating zone is greatly diminished relative to that with gas-phase reactions alone.

The corresponding stability limit derived from our previous approximate analysis[1] is also shown in Fig. 5 for each of the indicated values of θ_s. In general, the approximate treatment agrees with the exact one for small values of A_{DB}, and the agreement extends to larger values of A_{DB} as θ_s increases. In all cases, the approximate analysis tends to overestimate the zone of stable operation.

In almost all practical propellants the heat release in surface-coupled reactions probably represents at least 10 percent of the total, so that $\theta_s \gtrsim 1$. Moreover, for most propellants the decomposition activation energy is such that $A_{DB} < 5$, and the gas-phase flame temperature and activation energy are such that $1/\alpha_{DB} < 2$. Therefore, in the regime of greatest practical importance the approximate analysis is relatively close to the exact one.

The Steady Oscillatory Mode

In addition to the self-excited mode, which either grows or decays according to the criteria described above, there is a steady oscillatory mode of burning rate response to pressure perturbations. For a given value of θ_s, this mode is important in region a of Fig. 1, the region in which the self-excited mode decays and the propellant is technically stable. The steady-oscillatory mode is a constant-amplitude oscillation whose amplitude depends on the perturbation frequency and on the parameters A_{DB} and α_{DB}.

This behavior is illustrated for the specific case $\theta_s = 0.5$ in Fig. 6. Along the solid curves the ratio of maximum burning-rate amplitude to perturbation amplitude is constant and has the value shown. The perturbation frequency required to give this response is indicated by the dashed curves; any other perturbation frequency will result in a lower-amplitude response. The solid curve labeled ∞ corresponds to the limit line dividing regions a and b in Fig. 2. The zone beyond this curve is region b, in which a pressure disturbance of any characteristic frequency will induce an unstable response in the self-excited mode as described above.

It is evident from Fig. 6 that even with a propellant that falls well within the stable zone (region a of Fig. 2 if $\theta_s = 0.5$), a perturbation of a certain frequency, or a pressure decay whose characteristic time corresponds to that frequency, may cause an undesirable oscillatory response of greatly magnified amplitude unless the motor has a high damping factor. For example, a propellant with $\theta_s = 0.5$, $A_{DB} = 3$, and $1/\alpha_{DB} = 1.5$ is technically stable according to Fig. 1. However, if a pressure disturbance of frequency $\omega = 2\bar{r}^2/K$ is imposed, the amplitude of the burning rate response is more than four times that of the pressure disturbance, assuming the order of the gas-phase reaction $n \approx 2$. Thus, owing to this characteristic of the steady-oscillatory mode to be truly stable, a propellant must fall well inside the limit line between regions a and b corresponding to that propellant's characteristic value of θ_s.

CONCLUSION

Theoretical and experimental studies during this program have led to the inclusion of important, previously ignored phenomena in a combustion model that is reasonably realistic (consistent with available kinetics information), yet mathematically tractable. The early experimental studies suggested that the difference in solid-phase decomposition reactions for different composite propellants might lead to greater fractional heat release at the surface. Through an approximate analysis of the combustion model, it has been shown that the distribution of energy release between gas-phase and surface-coupled reactions may play a critical role in determining the stability bounds for a solid propellant.[1] The stability criterion derived from the approximate analysis, when presented in terms of pressure and burning rate, agrees qualitatively with experimentally observed stability limits.[1] A direct quantitative comparison cannot be attempted without precise kinetics data, which are not available, of course, for the complex propellant combustion mechanism.

To separate implications of the combustion model from possible limitations of the approximate mathematical analysis of that model,[1] the foregoing comparison with a more exact analysis was essential. In general, this comparison has confirmed our previous conclusions[1] qualitatively, and, to a rather surprising degree, quantitatively as well.

The analysis summarized above indicates that when even a very small fraction of the total heat release occurs in surface-coupled reactions, the likelihood of unstable combustion is greatly enhanced. The limitations indicated by the present analysis in this respect are somewhat more severe than those shown by the approximate treatment. The more exact analysis also shows the possibility of a high-amplitude burning rate response with certain pressure-disturbance frequencies, even when the propellant is technically stable (in the sense that there is no "runaway" burning rate response). This phenomenon has the effect of broadening the limit line into a narrow zone that separates clearly stable propellants from those that always tend to be unstable. The response of the propellants that fall within this dividing zone depends critically on the frequency of the pressure disturbance.

FUTURE WORK

It should be noted that the experimental studies are determining the magnitude of the losses which should be incorporated into a unified treatment of the propellant response and the gas dynamics of the cavity. Additional work is proceeding using adiabatic self-heating and DTA experiments to elucidate the different characteristics of solid-phase reaction for these propellants which exhibit contrasting stability behavior.

During our future theoretical studies we shall endeavor to modify the approximate solution previously developed[1] so that it is quantitatively closer to the more exact treatment outlined above. The latter is difficult to express in other than graphical form, and is therefore inconvenient for the purpose of obtaining an over-all description of instability bounds in rocket motors. On the other hand, it should be possible to combine equations for the transient gasdynamics of the combustion chamber with a suitably modified approximate analysis of the combustion model, expressed in equation form and encompassing all the important features mentioned above, to accomplish this objective.

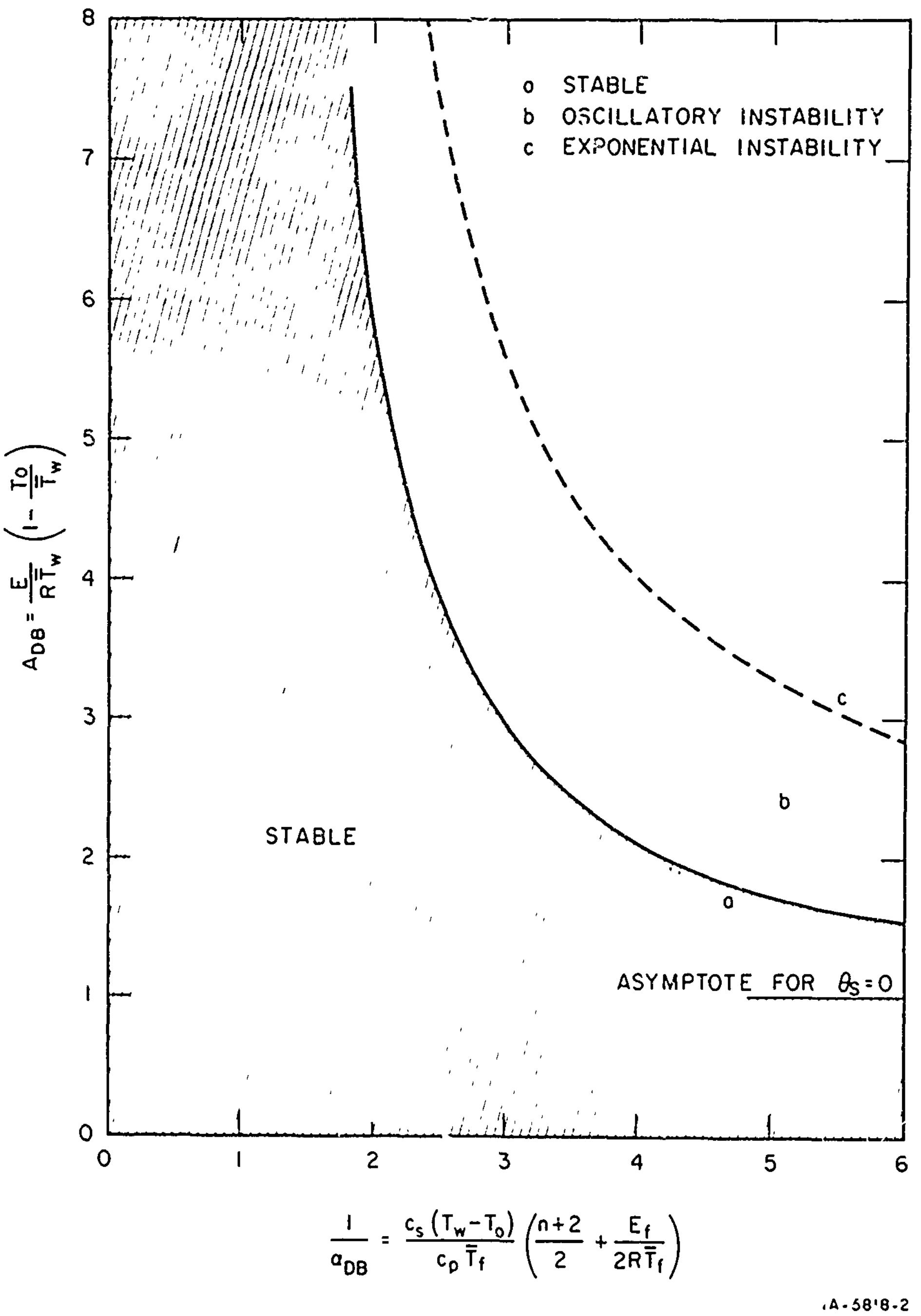

FIG. 1 STABILITY BOUNDS OF SELF-EXCITED MODE FOR $\theta_S = 0$

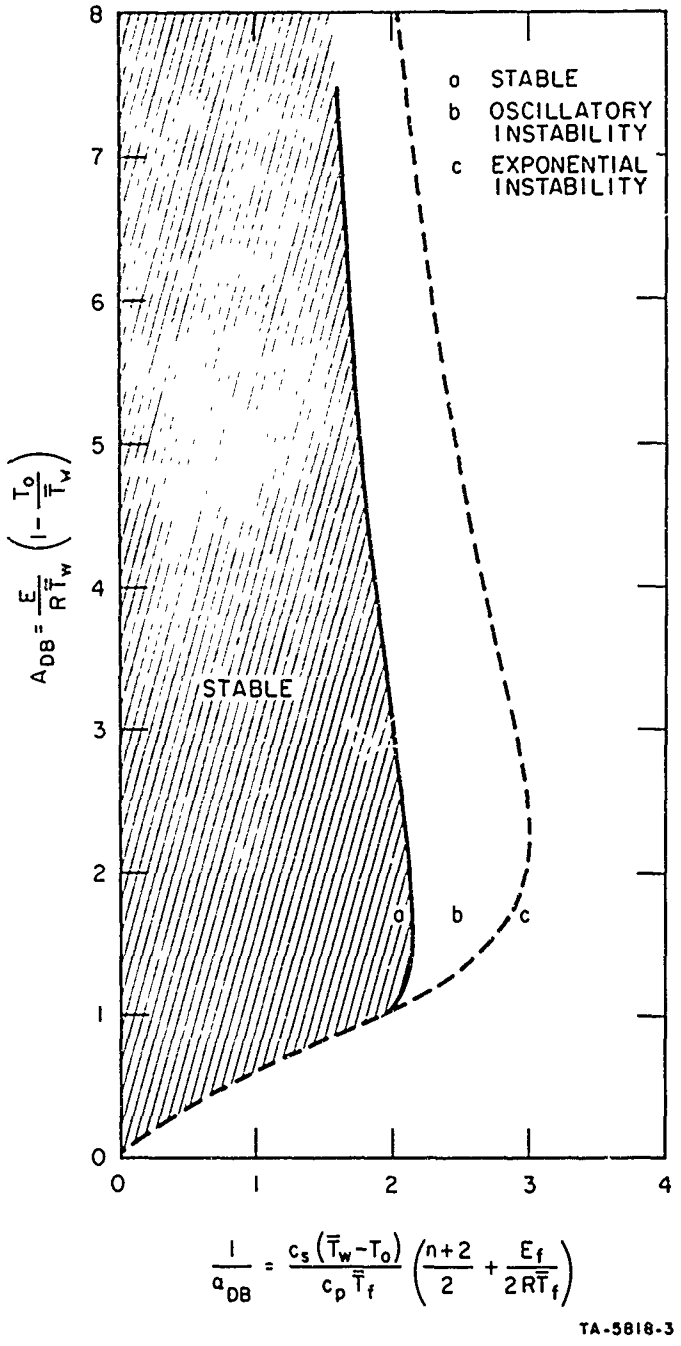

FIG. 2 STABILITY BOUNDS OF SELF-EXCITED MODE FOR $\theta_S = 0.5$

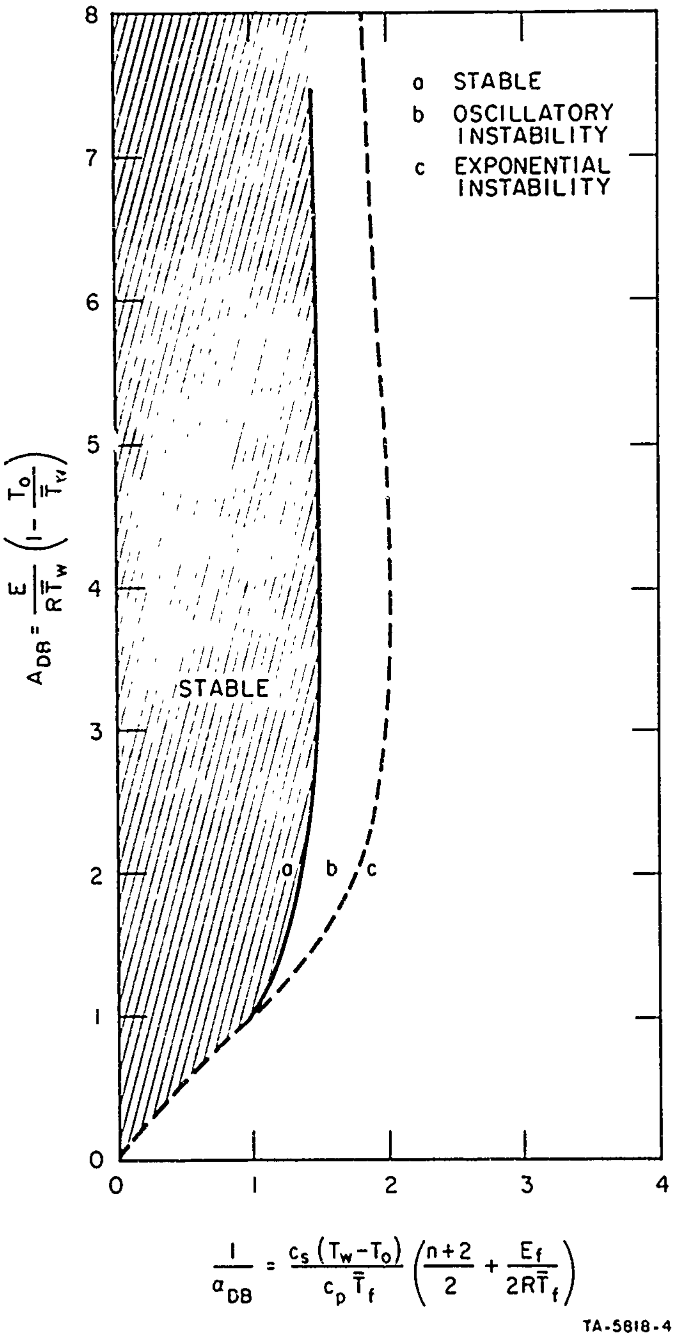

FIG. 3 STABILITY BOUNDS OF SELF-EXCITED MODE FOR $\theta_S = 1$

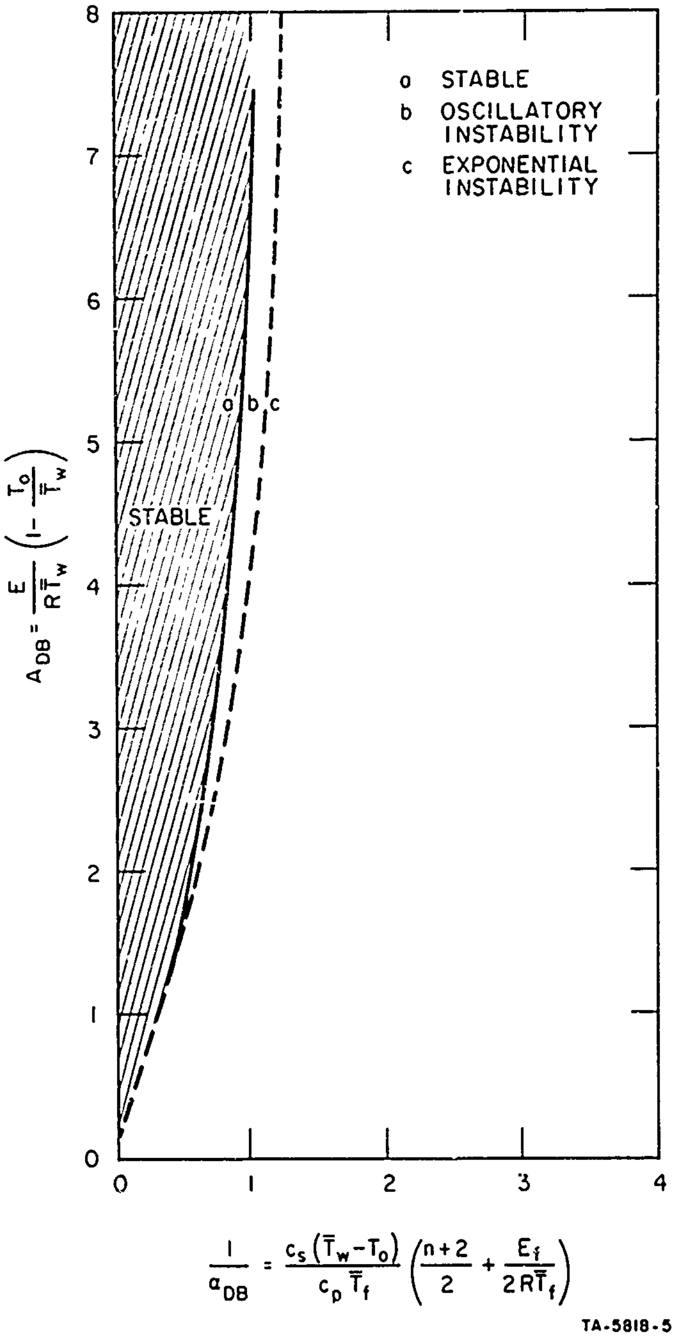

FIG. 4 STABILITY BOUNDS OF SELF-EXCITED MODE FOR $\theta_S = 3$

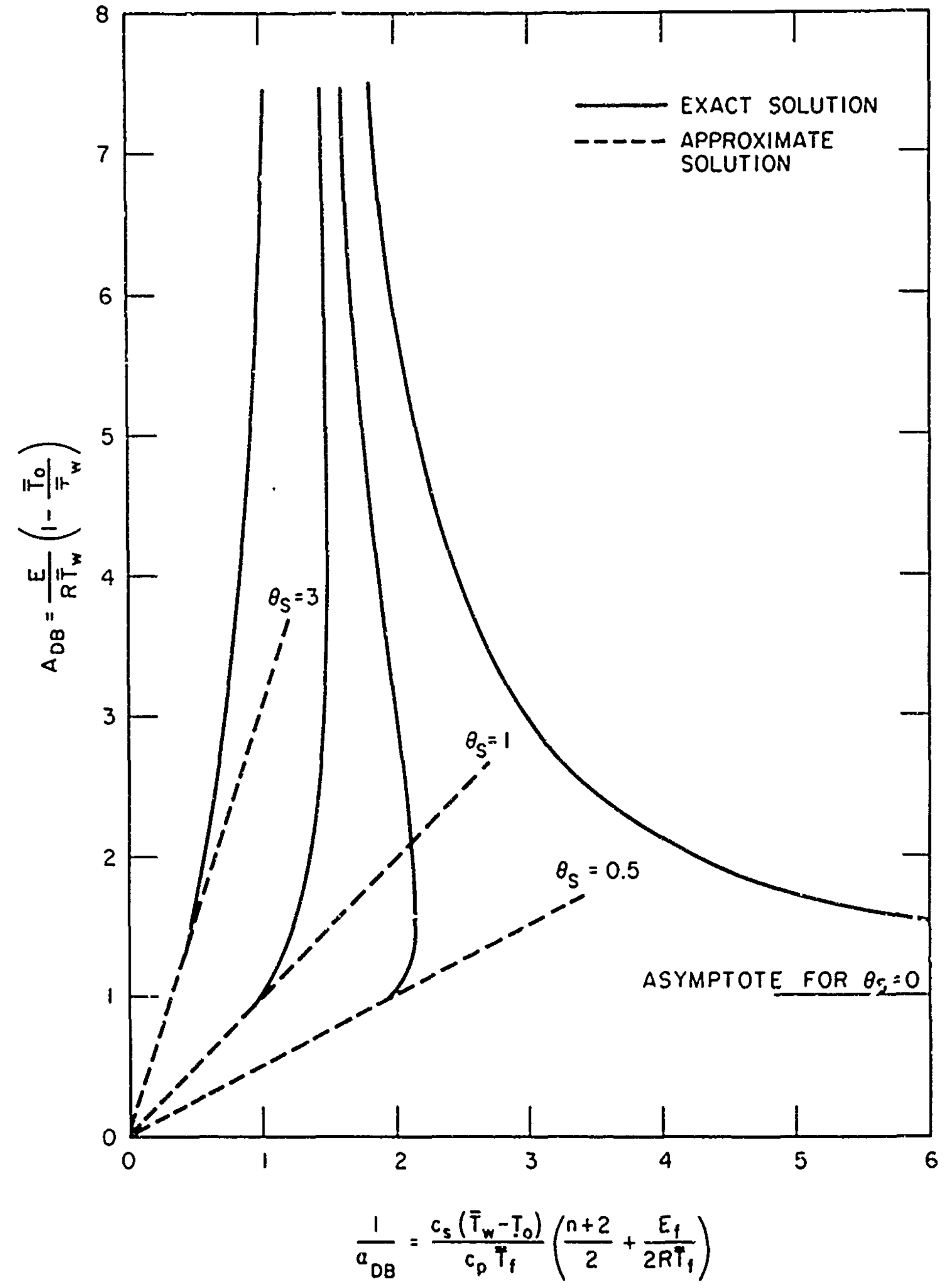

FIG. 5 COMPARISON OF APPROXIMATE AND EXACT STABILITY LIMIT

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13 ABSTRACT

Results of theoretical and experimental studies during this program of combustion instability of solid propellants are presented which have led to the inclusion of important, previously ignored phenomena in a combustion model that is reasonably realistic (consistent with available kinetics information), yet mathematically tractable. Through an approximate analysis of the combustion model, it is shown that the distribution of energy release between gas-phase and surface-coupled reactions may play a critical role in determining the stability bounds for a solid propellant. The stability criterion derived from the approximate analysis, when presented in terms of pressure and burning rate, agrees qualitatively with experimentally observed stability limits. To separate implications of the combustion model from possible limitations of the approximate mathematical analysis of that model, the foregoing comparison with a more exact analysis was made. In general, this comparison has confirmed previous conclusions qualitatively, and, to a rather surprising degree, quantitatively as well. The exact analysis indicates that when even a very small fraction of the total heat release occurs in surface-coupled reactions, the likelihood of unstable combustion is greatly enhanced. The limitations indicated by the present analysis in this respect are somewhat more severe than those shown by the approximate treatment. The more exact analysis also shows the possibility of a high-amplitude burning rate response with certain pressure-disturbance frequencies, even when the propellant is technically stable (in the sense that there is no "runaway" burning rate response). This phenomenon has the effect of broadening the limit line into a narrow zone that separates clearly stable

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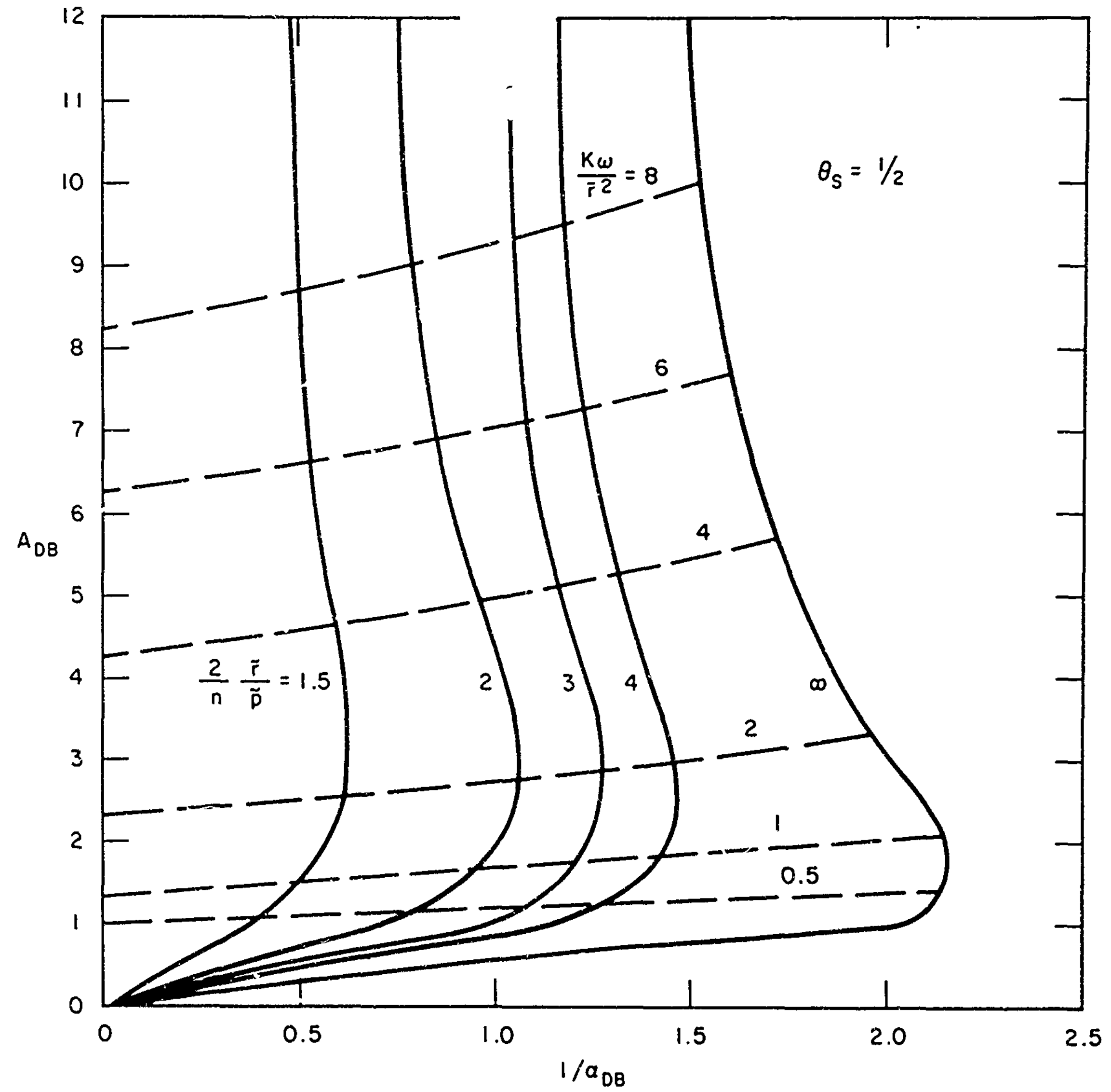

FIG. 6 AMPLITUDE OF STEADY-OSCILLATORY MODE FOR $\theta_S = 0.5$

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Solid Propellant Combustion Instability						
Combustion						
Erosive Transients						
Unstable Burning						
Oscillatory Combustion						
Axial Instability						
Transverse Instability						
Ammonium Perchlorate						
Composite Propellant						
Gas Dynamics						
Combustion Response						

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