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TECHNICAL PAPER presented at Fourth Combustion
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## ABSTRACT

An experimental investigation was conducted to learn more about how certain specific details of a concentric tube injection element effect the screech characteristics of a hydrogen-oxygen rocket. The five variables investigated were (1) injection angle, (2) oxidizer tube blunt base thickness, (3) oxidizer tube recess and extension, (4) oxidizer tube-annulus concentricity, and (5) element size or thrust-per-element. Tests were made using a 10.77-inch diameter heat-sink combustor at nominally 300 psia chamber pressure. The effects of the element detail changes on screech are summarized by first noting that these modifications resulted in changes in injector differential pressure even though the physical injection area was constant for all similar tests. Second, changes resulting in increased injector differential pressure produced improved screech stability. These data trends were compared with a hydrogen flow response model and were found to be in agreement.

## INTRODUCTION

As evidenced by the extensive development programs required--almost without exception--in achieving flight qualification, the rational design of new liquid bipropellant rocket engines remains an objective. For hydrogen-oxygen propellants and concentric tube type injector elements, a substantial pool of knowledge has been acquired from many sources. This information was exploited to the fullest in arriving at the M-1 design configuration; nevertheless, considerable judgment was required to bridge gaps in existing knowledge. Furthermore, it was recognized that certain detailed design variables of potential importance had to be chosen with little or no information regarding their effects on combustion stability.

The major objective of the present work was to provide design guidance regarding the sensitivity and trends of stability as a function of some of the element detail variables about which little or no information existed. Most of the data are compared with an instability theory proposed by Feiler and Heidmann (ref. 1) which considers the ability of the fuel injector to respond to pressure perturbations.

The following design variables were investigated experimentally over the ranges indicated:

A. With a 157 element concentric tube injector - 20K thrust
    1. Injection angle between annular hydrogen stream and oxidizer jet . . . . 0 to 45°
    2. Oxidizer tube blunt base thickness . . . . 0.014 to 0.068 inches

3. Oxidizer tube recess and extension . . . . -0.33 to +1.25 inches
4. Oxidizer tube eccentricity

B. With a 421 element concentric tube injector - 20K thrust
Oxidizer tube recess . . . . . . . -0.5 to 0.0 inches

C. With 8 to 1000 element concentric tube injectors
Thrust-per-element . . . . . . . 2500 to 20 pounds

## PROCEDURE

The stability of each configuration was expressed in terms of the hydrogen injection temperature at which screech was encountered. This temperature rating was accomplished by varying the amount of $50^{\circ}$R liquid hydrogen and ambient temperature gaseous hydrogen in a mixing tube to produce a downward temperature ramp. Constant total weight flow was maintained (constant mixture ratio) while the temperature of the injected hydrogen was reduced below the anticipated screech limit. The screech limit was defined as the instantaneous hydrogen injection temperature corresponding to the initiation of high frequency pressure oscillations with an amplitude greater than the noise level of stable combustion. Data were obtained over a range of oxidant-fuel ratios to establish a stability limit curve.

## RESULTS AND DISCUSSION

In the discussion to follow, the experimental results are considered for each of the element detail variables investigated. Correlation of some of these results with an existing theoretical model was found and will be discussed with the first configuration presented, then mentioned where applicable with other configurations.

Effect of Injection Angle. Injection angle for a concentric tube element was defined as the angle between the axis of the oxidizer tube and the impinging annular fuel stream. As shown in Fig. 1, the hydrogen injection temperature at transition to screech (transition temperature) was reduced (stability improved) with increasing injection angle. The effect of injection angle on characteristic exhaust velocity efficiency is also shown in Fig. 1 to be insignificant.

Although the physical hydrogen injection area was constant for each of the configurations tested, the injector differential pressure schedule varied with injection angle. More specifically, as the injection angle increased, the injector differential pressure (at the same flow rate and temperature) also increased. Considering an increase in pressure drop as representing an increase in flow resistance, the theoretical response model of Ref. 1 predicts an improvement in stability so long as the inertia and capacitance terms remained constant--a condition which was approximated for the data presented above. Another way of describing the stabilizing effect of increased injection angle (and one which lends itself to comparison of velocity ratio and injection area ratio correlations of ref. 2) was to equate the increased pressure drop (resistance) to an effective hydrogen injection area, $A_{eff}$. Figure 1 indicates that as injection angle is increased, there is a decrease in the ratio of effective area to the physical injection area, $A_{eff}/A$.

Oxidizer Tube Blunt Base Thickness. Oxidizer tube blunt base thickness was defined as the thickness of the oxidizer tubes separating the two propellants at the injector face. A sketch of the configurations tested, as well as the stability and combustion performance data, are shown in Fig. 2. The data indicate a critical thickness which corresponds to minimum combustion stability. Both increasing and decreasing the thickness from this critical value improved stability. There was no significant change in characteristic exhaust velocity efficiency over the range of thickness tested.

The question was raised, however, that the necessary changes in the hydrogen flow passages may also have effected the results. But regardless of the purity of the test, the $A_{eff}/A$ data indicate that increasing the injector differential pressure does improve stability.

Oxidizer Tube Recess and Extension. Recessing the oxidizer tubes of a 421 element injector was found to have a strong stabilizing effect. The screech limit improved sharply until, with a recess depth of 0.5 inches, complete stability was obtained down to the minimum temperature limit of the test facility (fig. 3). There was, however, a slight decrease in combustion performance corresponding to the improved stability (fig. 3). A 157 element injector was stabilized when the recess depth was increased to 0.33 inches (fig. 4). Also, it is shown in the figure that extending the oxidizer tube up to 0.75 inches caused both the combustion stability and performance to decrease. With an extension of 1.25 inches, instability was not encountered even at $55^{\circ}R$, however, the performance was decreased markedly.

The trend of improved stability with increased injector pressure drop is shown in Figs. 3 and 4 by noting the trend of $A_{eff}/A$ with recess.

Oxidizer Tube Eccentricity. Two configurations were tested. One using washers to insure concentricity of the oxidizer tubes and fuel annuli, and the other with no washers and, therefore, a random concentricity due to normal manufacturing tolerances. The results are shown in Fig. 5 and indicate that concentricity is not a critical consideration for stability.

Effect of Thrust-per-Element. Hydrogen injection temperature is shown as a function of thrust-per-element in Fig. 6. No instability was encountered above a thrust-per-element of 100 pounds. The stability limit of injectors with thrust-per-element of 100 pounds or less is correlated in Fig. 7 by the parameter velocity ratio times total propellant flow rate per element, $VR\ W_p/E$. Characteristic exhaust velocity efficiency is shown as a function of hydrogen injection temperature in Fig. 8 for a range of thrust-per-element of 20 to 2500 pounds. As the momentum of the hydrogen is decreased by decreasing the hydrogen injection temperature, there was a resulting decrease in performance. Comparison of the two 2500-pound thrust-per-element configurations indicates, however, that with proper design and development, a respectable level of performance may be obtained even for these coarse elements (ref. 3).

## SUMMARY OF RESULTS

Within the range of variables and test conditions investigated, the following results were obtained:

1. By use of the response factor model of Ref. 1, the long observed effect of hydrogen temperature on screech limits of hydrogen-oxygen rockets is explained as being due to the change in injector resistance.

2. Similarly, changes in stability due to changes in injection velocity ratio are also explainable through the mechanism of changes in injector hydrogen flow resistance.

3. As the impingement angle of concentric tube injectors was increased from zero (parallel flow) to 45°, stability was improved with no effect on performance.

4. The data for oxidizer tube blunt base thickness effect indicate a critical thickness which corresponds to minimum stability but the necessary changes in the hydrogen flow passages may also have effected the results.

5. Recessing of the oxidizer tubes improved stability continuously with depth until completely stable configurations were achieved (with elements of two different sizes). For the coarser elements, efficiency also improved but the fine elements produced a slight decay in efficiency.

6. Progressive extension of the oxidizer tubes into the thrust chamber decreased both stability and efficiency until a discontinuity occurred. Beyond the discontinuity, operation was completely stable but efficiency was markedly reduced.

7. In regard to concentricity of the oxidizer tubes in the hydrogen annuli, no significant effect was found.

8. A broad range of thrust-per-element data were correlated with the parameter $[VR\ W_p/E]$.

## REFERENCES

1. Feiler, Charles E.; and Heidmann, Marcus F.: Dynamic Response of Gaseous-Hydrogen Flow System and its Application to High-Frequency Combustion Instability. NASA TN D-4040, 1967.

2. Wanhainen, John P.; Parish, Harold C.; and Conrad, E. William: Effect of Propellant Injection Velocity on Screech in a 20,000-Pound Hydrogen-Oxygen Rocket Engine. NASA TN D-3373, 1966.

3. Hannum, Ned P.; and Conrad, E. William: Performance and Screech Characteristics of a Series of 2500-Pound-Thrust-Per-Element Injectors for a Liquid-Oxygen-Hydrogen Rocket Engine. NASA TM X-1253, 1966.

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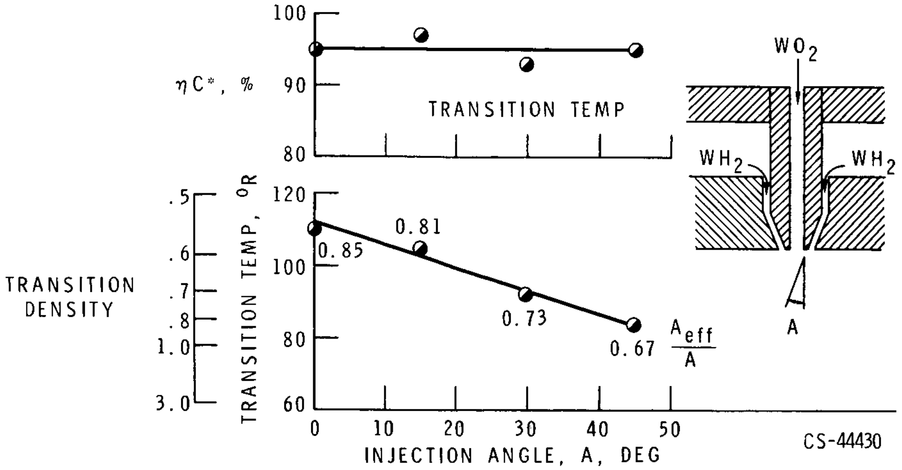

Figure 1. - Injection angle effect, 157 element injector, O/F = 5.0.

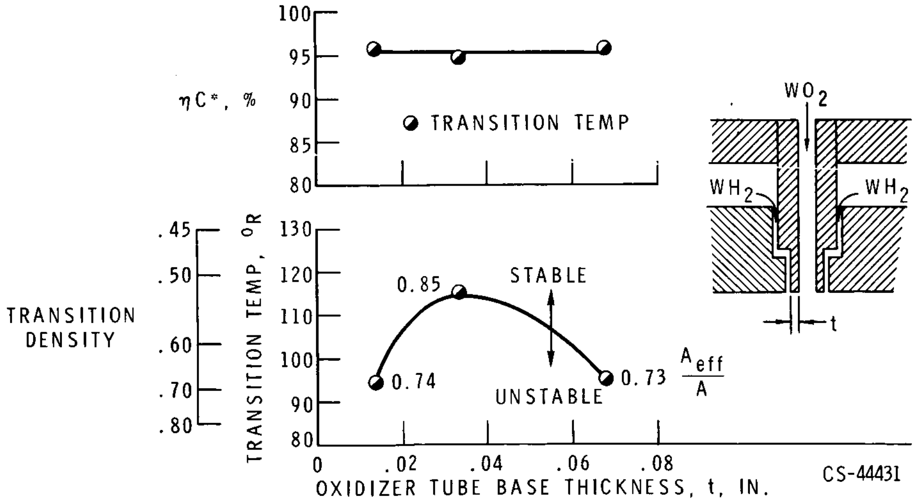

Figure 2. - Oxidizer tube base thickness, 157 element injector, O/F = 5.0.

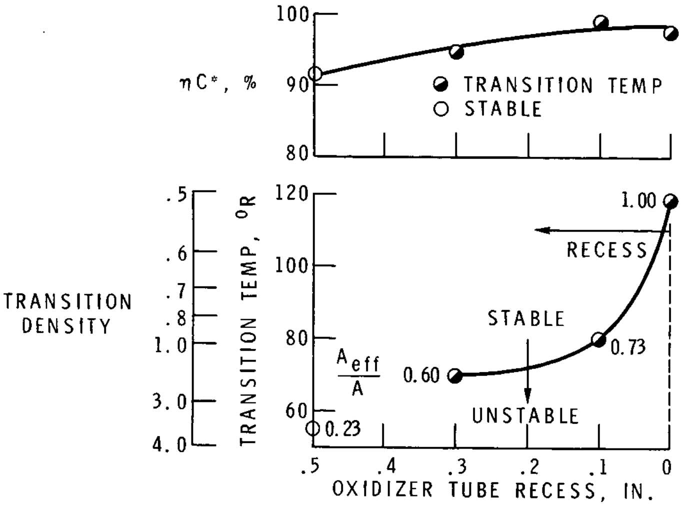

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Figure 3. - Oxidizer tube recess effect, 421 element injector - 15° tubes.

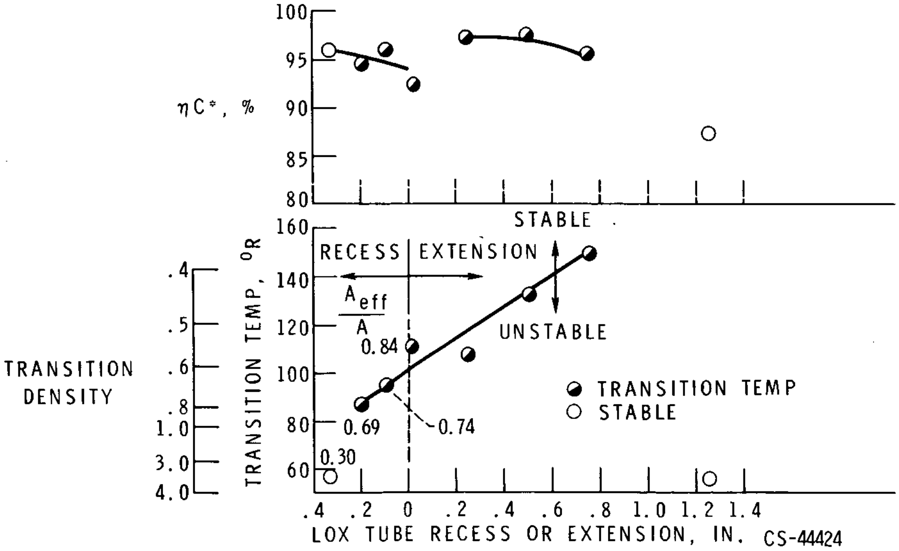

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Figure 4. - Effect of lox tube recess and extension. O/F = 5.0, 157 element, parallel streams.

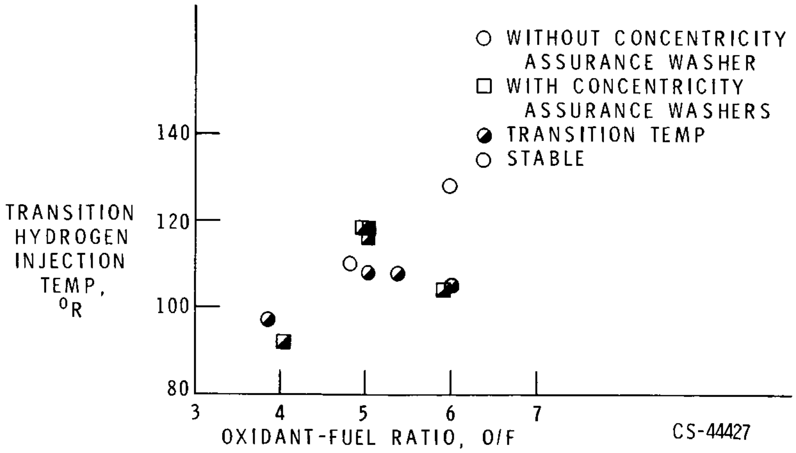

Figure 5. - Effect of eccentric oxidizer tubes, 157 element injector.

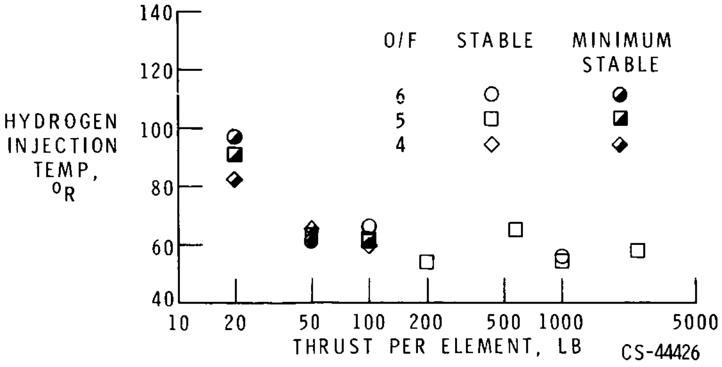

Figure 6. - Effect of thrust per element on minimum hydrogen temperature.

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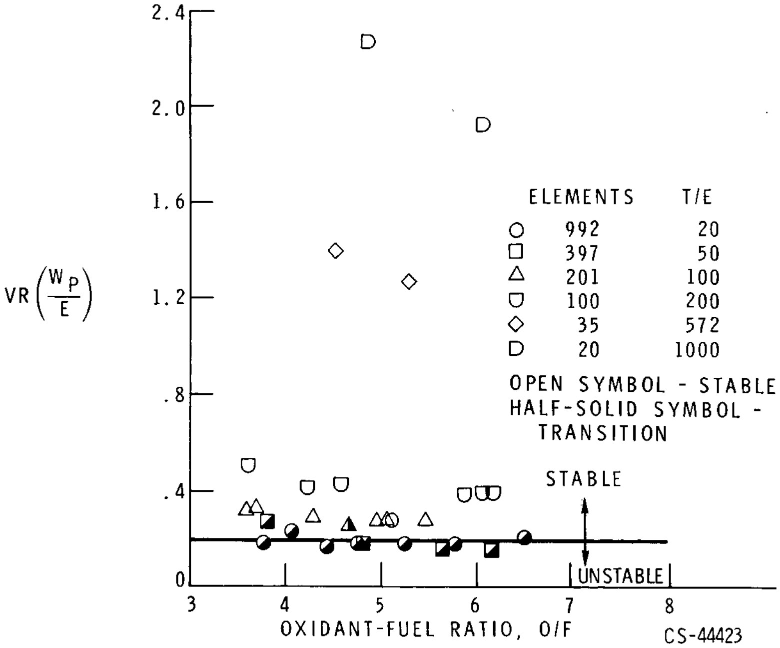

Figure 7. - Variation of VR $\left(\frac{W_P}{E}\right)$ with O/F for all injections tested.

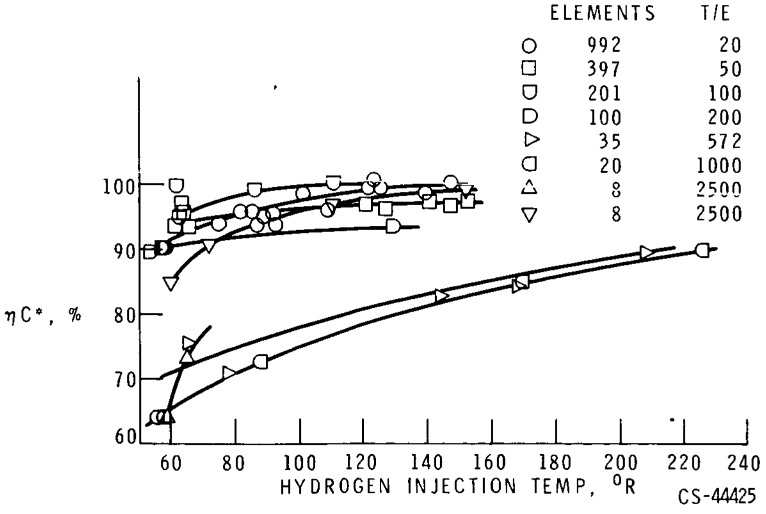

Figure 8. - Effect of hydrogen inlet temperature on combustion efficiency.